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The Use of Prototypes in Selected Foreign Fighter Aircraft Development Programs

Rafale, EAP, Lavi, and Gripen

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RAND | NATIONAL DEFENSE RESEARCH INSTITUTE

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This report surveys and compares the approaches to prototyping adopted by four countries--Great Britain, France, Israel, and Sweden--during the development of similar new fighter/attack aircraft. It is based primarily on information gathered during interviews and briefings conducted in 1987 with senior government and industry officials of those countries. Basic fighter airframe development still carries sufficient risks and uncertainties to warrant the manufacture and flight testing of an austere airframe prototype before full-scale development (FSD). However, avionics development and integration are becoming areas of increasingly high technological complexity, uncertainty, and risk. Effective development and adequate testing and integration may be possible only with the help of sophisticated avionics ground labs and with fully missionized prototypes that are essentially pre-production FSD engineering test articles. A combination of both pre-FSD austere prototyping and missionized prototyping may be required to meet the challenges arising in the acquisition environment of the late 1980s. (Sw)

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The Use of Prototypes in Selected Foreign Fighter Aircraft Development Programs

Rafale, EAP, Lavi, and Gripen

Mark A. Lorell
with Donna Kim Hoffman

September 1989

Prepared for the
Assistant Secretary of Defense
(Production and Logistics)

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PREFACE

In 1987 RAND began a research effort sponsored by the Assistant Secretary of Defense (Acquisition and Logistics)—now the Assistant Secretary of Defense (Production and Logistics)—aimed at identifying, defining, and analyzing a range of system and subsystem prototyping strategies that meet Department of Defense requirements for new prototyping approaches suitable to the changed acquisition environment of the late 1980s. This research effort, entitled the "Prototyping Strategies Project," was conducted under the Acquisitions and Support Policy Program within RAND's National Defense Research Institute, an OSD-supported federally funded research and development center.

As part of that effort, this report examines and assesses the prototyping strategies adopted for four major foreign fighter aircraft development programs: the British EAP, the French *Rafale*, the Israeli *Lavi*, and the Swedish *Gripen*. This report should be of interest to officials and analysts inside and outside government concerned with improving the efficiency of the U.S. weapon systems acquisition process.

SUMMARY

This report surveys and compares the different national approaches to prototyping adopted by four foreign countries—Britain, France, Israel, and Sweden—during the development of similar new fighter/attack aircraft.[1] In part as a response to the recommendations to the President's 1986 Blue Ribbon Commission on Defense Management, U.S. Department of Defense (DoD) acquisition guidelines now recommend prototyping systems or subsystems during the concept validation phase before the decision to enter into full scale development (FSD). Advocates of this strategy assert that flight testing low-cost, stripped-down airframe/engine prototypes reduces technological uncertainties, illuminates questions of military utility, improves cost and performance estimations, and in general provides more reliable information on which to base a decision to enter into FSD. Such information, it is claimed, lessens the likelihood of unexpected and extremely costly technical problems and delays arising during FSD.

Critics have raised questions about the continuing utility of austere low-cost airframe prototyping before FSD; they argue that changing technology trends and new military requirements have made development and integration of subsystems—particularly avionics—the areas of highest technological risk and operational uncertainty. They allege that only FSD engineering test articles or pre-production prototypes that are as close to the final production article as possible are capable of contributing to the full development and integration of critical subsystems. Such prototypes, by definition, can be built and tested only during FSD and as a part of it.

As one means of examining these issues, we questioned senior government and industry officials currently involved in four major foreign fighter R&D programs: the Dassault *Rafale* A,[2] the British Aerospace (BAe) EAP, the Israel Aircraft Industries (IAI) *Lavi*, and the Industry Group (IG) JAS *Gripen*. These four programs represent two different philosophical approaches to the use of prototypes:

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[1]It is based primarily on information gathered during an extensive series of interviews and briefings conducted in the summer and fall of 1987 with senior government and industry officials representing the four above-mentioned countries.

[2]The *Rafale* technology demonstration prototype received its "A" designation only after the definition of the considerably smaller production version, which Dassault labelled *Rafale* D. Unless otherwise noted, the name *Rafale* alone is always used here to refer to the pre-FSD "A" prototype.

- The *Rafale* A and EAP programs reflect a philosophy of building and flight testing basic unequipped airframe prototypes before FSD.
- The *Lavi* and *Gripen* programs dispensed with pre-FSD prototypes; they opted for a total weapon system development concept based on fully equipped "missionized" engineering test or pre-production prototypes built and tested after the beginning of FSD.

Although formally labeled technology demonstrators, both the *Rafale* A and EAP closely resemble traditional pre-FSD austere airframe prototypes. The sponsoring governments provided no guaranteed financial support for flight testing (in the case of the EAP) and absolutely no commitment to FSD, much less production. Both aircraft were financed on a shoestring and were bereft of virtually all major subsystems, avionics, and weapon systems. Furthermore, both prototypes benefited from incremental development of key technologies on earlier test-beds or prototypes. Small design teams with little government oversight or interference were permitted wide latitude to experiment with creative technical solutions, without the restrictions of detailed government specifications.

In short, these two aircraft are indeed the modern corollaries of the austere, incremental airframe prototypes of the 1950s. And as development projects, these two programs clearly benefited from this approach: Both aircraft first flew about six months ahead of schedule and met or surpassed performance and cost expectations. Dassault and EAP managers have concluded that their use of austere pre-FSD airframe prototypes:

- provided unique opportunities to experiment with technologies, applications, and concepts that otherwise would have been forgone on a FSD prototype because the risks and costs of failure would have been perceived as much greater;
- permitted proof-testing and refinement of complex technological issues in a much more informal and lower-cost environment, allowing a much greater level of confidence to be reached for estimates of technological risk, military utility, and FSD costs before authorization of FSD.

These advantages, program managers argue, applied especially to the areas of aerodynamic configuration and flight control systems, exotic and advanced materials and structures, and cockpit design and pilot ergonomics. Other areas also benefited: digital engine control, radar absorbing materials, and data bus development to name a few.

The IAI *Lavi* and Saab-Scania JAS 39 *Gripen* programs are in many respects examples of a development approach fundamentally at odds with the precepts of early pre-FSD austere airframe prototyping and associated concepts applied to the development of the *Rafale* and EAP. The Israeli and Swedish programs were structured in accordance with the following hypotheses:

- Advances in computer simulation and the development of sophisticated design aids such as Computer Assisted Design/Manufacture (CAD/CAM), combined with intensive wind tunnel testing, have greatly reduced the technological risk and uncertainties associated with basic airframe development, rendering austere pre-FSD airframe/engine prototypes unnecessary.
- The development and integration of extremely sophisticated interactive avionics systems, it is argued, have become by far the highest risk technology area in modern fighter development programs. Reduction of uncertainties in these areas can be accomplished only through avionics integration labs and the testing of fully missionized FSD engineering test vehicles, that by definition can only be manufactured during, and as an integral part of, FSD.

The first hypothesis clearly needs to be qualified, given the actual experience of the *Lavi* and *Gripen* developers. Anticipating that only minor detail changes would be required to the basic airframes based on the results of flight testing, IAI and IG JAS froze their designs early on and committed to production tooling and the procurement of long-lead items. Following more extensive wind-tunnel, static, and flight testing, IAI and IG JAS both discovered major flaws in some of their assumptions regarding design configuration and fabrication of large composite airframe structures. These problems contributed to serious delays in the development of flight control hardware and software, resulting in substantial cost growth and overall program schedule slips of as much as two years or more.

One lesson of these two programs is that

- **there are still areas of considerable technological risk and uncertainty in basic air vehicle development that can't be reduced to insignificance through computer simulations and wind-tunnel testing alone.**

In many respects the success (at least in the early phases of their programs) of Dassault and BAe compared with IAI and IG JAS arises not only from their early use of austere pre-FSD prototypes, but also from the adoption of a broader acquisition strategy incorporating companion concepts often associated with austere prototyping of the sort traditionally practiced by Dassault. Many of the problems experienced by the Israelis and the Swedes during the first phases of FSD, when they were concentrating on the nonmissionized flight test vehicles, appear to be related to their failure to adhere to these companion precepts, most especially

- R&D incrementalism and
- avoidance of program concurrencies.

The two sets of programs reviewed in this report present stark contrasts in program phasing: The *Lavi* and *Gripen* programs are total system approaches characterized by numerous R&D and production concurrencies, while the *Rafale* A and EAP are components of "phased" programs with more distinct and separate concept validation, FSD, and production periods. The Israeli and Swedish programs attempt to develop the airframe and all subsystems simultaneously while concurrently gearing up for production.

Management style and organization also seem to play a role in the comparative success of these programs. Program officials developing both the *Rafale* A and EAP are convinced that the approach using flexible, lean management and R&D teams and burdened with minimal government interference and oversight benefited their programs immensely. They particularly applaud the decision of their governments to forgo detailed technical specifications and reporting requirements as a high-leverage means of enhancing program efficiency.

In conclusion, what these programs tell us is that in certain circumstances

- **basic airframe development still carries sufficient risks and uncertainties to warrant the manufacture and flight testing of an austere airframe prototype before FSD.**

But these programs do not necessarily invalidate all the concepts behind the Israeli and Swedish approaches. The sorts of problems beginning to be encountered on all current fighter development programs suggest that:

- **avionics development and integration are becoming areas of increasingly high technological complexity, uncertainty, and risk. Effective development and adequate testing and integration may be possible only with the help of sophisticated avionics ground labs and with fully missionized prototypes that are essentially preproduction FSD engineering test articles.**

Since avionics development costs may rise to 50 percent or more of total R&D costs, determining the most efficient avionics development and integration strategies is critically important.

Use of an R&D strategy employing early pre-FSD austere airframe prototyping and other associated concepts can substantially reduce uncertainty in the early phases of FSD, but it may not be sufficient to assure a successful fighter R&D effort overall *unless other strategies* are adopted that are specifically tailored to the problems of avionics and other subsystem development and integration.

These strategies may include extensive testing with a fully missionized engineering test article that duplicates the final production version as closely as possible. But austere pre-FSD prototyping probably will be of little use in this area. Along with the incorporation of "phased" acquisition and initial low-rate production to reduce the costs and disruption of changes flowing from operational testing,

- **a combination of both pre-FSD austere prototyping and missionized FSD prototyping may be required to meet the challenges arising in the acquisition environment of the late 1980s.**

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- Olin Marketing and Aeronautical Consulting AB, Taby, Sweden
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Any errors in interpretation or fact are our sole responsibility.

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I. INTRODUCTION

This report surveys and compares the different national approaches to prototyping adopted by Britain, France, Israel, and Sweden during the development of new fighter/attack aircraft. It is part of a larger RAND research effort aimed at identifying, defining, and analyzing a range of system and subsystem prototyping strategies that meet Department of Defense (DoD) requirements for prototyping approaches suitable to the acquisition environment of the late 1980s. It is based primarily on information gathered during an extensive series of interviews and briefings conducted in the summer and fall of 1987 with senior government and industry officials representing the four above mentioned countries.[1]

In 1986, the President's Blue Ribbon Commission on Defense Management, chaired by former Secretary of Defense David Packard, urged in its final report that DoD modify its policies and regulations to "require the testing of prototype systems and subsystems before the authorization of full-scale development (FSD)."[2] In the view of the Packard Commission, the principal benefits of early prototyping include more realistic cost estimating and an improved understanding of the operational feasibility and military utility of new technologies before commitment to FSD and production. In part as a response to this recommendation of the Packard Commission, DoD acquisition guidelines were modified in September 1987 to incorporate "prototyping of the system or selected system components" as a "primary consideration" during the concept validation phase before the decision for FSD.[3]

A key component of the Packard Commission's recommendations regarding prototyping was the insistence that it be undertaken before FSD. FSD is usually defined as a clear commitment, normally in the form of a government contract, to develop and engineer a fully equipped, missionized pre-production article on hard tooling; it often encompasses actual low-rate production. FSD is routinely viewed as a de facto government commitment to production and procurement of a weapon system. If unexpected technical or operational difficulties are uncovered after this point, the cost in money and time of correcting

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[1]See the Acknowledgments for a complete listing of the organizations visited.

[2]The President's Blue Ribbon Commission on Defense Management, 1986, p. 32.

[3]DoD Instruction 5000.2, "Defense Acquisition Program Procedures," *Federal Contract Reports*, Vol. 48, September 14, 1987, p. 369.

them can be substantial, since series production on hard-tooling may already have begun, requiring major retrofit or redesign of production articles. Pre-FSD prototyping is seen as a technique to reduce the likelihood of this problem, by testing out technologies and operational concepts with actual hardware and test items so that potential problems can be pinpointed early and appropriate corrective action can be taken more cheaply and easily before a major commitment to FSD and production.

Virtually since the cessation of routine system prototyping of fighter/bomber aircraft in the mid-1950s, acquisition reformers have consistently advocated a return to prototyping to reduce technology and cost uncertainties early in fighter and other major weapon system R&D programs. This was particularly true after the unhappy experience in the 1960s of massive cost overruns, schedule delays, and performance shortfalls suffered by the F-111 fighter-bomber and C-5A military transport programs. Program managers had structured these development efforts in accordance with Secretary of Defense Robert McNamara's new "total system" acquisition concept that eschewed pre-FSD system prototyping and hardware proof testing, relying instead only on paper studies and simulations to support the decision for FSD and production.[4]

In the wake of the procurement scandals of the 1960s, Deputy Secretary of Defense David Packard attempted to revamp and reform the acquisition process in the early 1970s. Numerous contemporary studies indicated that prototyping of fighter aircraft before FSD could reduced R&D cost growth, schedule delays, and performance shortfalls, while apparently adding little to program length or cost.[5] Packard's proposed acquisition reforms drew heavily on these and other studies, focusing on the concept of "fly-before-buy," which emphasized hardware demonstration, performance testing, and prototype competitions.[6] Ultimately these principles were applied in whole only to a handful of systems developed in the 1970s and into the 1980s. But where they were applied, as in the case of such programs as the Attack-Experimental (AX) aircraft and the Lightweight Fighter (LWF), the evidence suggested that prototyping could improve the quality of program decisionmaking by reducing technological and operational uncertainties before FSD, thereby decreasing the likelihood of unexpected or

[4]For example, see Coulam, 1977.

[5]Throughout this period The RAND Corporation made a particularly notable contribution to the acquisition literature on prototyping, beginning with Klein et al., 1958. The findings of RAND research conducted during the 1950s and 1960s are summarized in Perry, 1971, 1972.

[6]See Perry, 1980; Deagle, 1980.

undesirable program outcomes after the commencement of FSD.[7] It was such considerations that underpinned the 1986 recommendations of the President's Blue Ribbon Commission on Defense Management and the 1987 DoD acquisition guidelines that place a renewed emphasis on pre-FSD prototyping and hardware testing.

Yet, various acquisition and technology trends in recent years involving fighter aircraft development have cast doubt in the minds of some observers on the continuing efficacy of the traditional pre-FSD prototype approach to fighter aircraft development. In modern fighter/attack aircraft, avionics and other subsystems have become increasingly important relative to the airframe/engine combination. Weapon systems have become much more complex and the subsystem integration more important. The latter can generally be accomplished only after the onset of FSD. It is often argued that advances in computer simulation and the development of sophisticated design aids such as CAD/CAM,[8] combined with intensive wind tunnel testing, have greatly reduced the technological risk and uncertainties associated with basic airframe development. Further, the declining rate of advancement of airframe/engine performance demands combined with rising unit costs and much longer inventory lives mean that far fewer entirely new air vehicles will be—or need to be—developed and deployed.[9] As a result, some critics of the Packard commission have argued that pre-FSD prototyping is now too expensive and technologically neither necessary nor relevant to the really high-risk aspects of modern weapon system development programs; therefore it should not be applied routinely to major fighter aircraft R&D efforts.

Historically the concept of pre-FSD prototyping; when applied to fighter/attack aircraft, has often been closely associated with the notion of *austere* prototyping, which usually refers to a hand-built, custom-made airframe-engine test vehicle that closely resembles, but is not necessarily identical to, the ultimate production article. Most important, the austere prototype is not *missionized*; that is, it lacks all combat avionics, subsystems, and components required to transform the aircraft into a fully combat-capable weapon system. The purpose of an austere prototype is to permit proof-of-concept testing of technical and operational aspects of the basic airframe/engine combination, avoiding all the cost and complexity of testing a prototype with such components as a radar and a weapons management computer. Indeed,

[7]Following competitive prototype flyoffs, these two programs ultimately resulted in the procurement of the A-10 attack aircraft and the F-16 fighter-bomber. See Smith et al., 1981; and Rich et al., 1986.

[8]Computer assisted design and computer assisted manufacturing.

[9]Rich, 1986.

advocates of this approach argue that a fully missionized prototype requires full-scale development and therefore technically is not a prototype at all, but a pre-production engineering test article. To such advocates, austerity must be combined with prototyping if the anticipated benefits of proof-testing before FSD are to be enjoyed.

But modern critics of austere pre-FSD prototyping counter that because of recent trends in technology referred to above, the development of the basic engine/airframe combination for conventional fighter/attack aircraft has become a fairly low risk aspect of an overall development program[10] More important, critics of pre-FSD austere prototyping insist that the development and integration of extremely sophisticated interactive avionics systems is by far the highest risk technology area in modern fighter development programs. Reduction of uncertainties in these areas is best accomplished through avionics integration labs and through the testing of fully missionized engineering test vehicles. They argue that:

- The most useful prototype is fully missionized, flight tested throughout, and an integral part of the full-scale development process. Austere, pre-FSD prototypes in the classic sense are no longer feasible or useful and are indeed a waste of scarce budgetary resources and time.

With an overview of this debate as background, we survey the recent experiences of four foreign governments and their national industries with major fighter aircraft development programs as part of our research effort to help determine the most appropriate method of prototyping fighter/attack aircraft in the circumstances of the late 1980s. We believe that questioning senior development managers and officials of major foreign fighter development programs in countries with good R&D track records can produce useful insights regarding prototyping as an acquisition strategy and tool. Whether their views accurately reflect reality and are applicable to the U.S. environment are matters of subjective judgment.[11]

[10]Conventional aircraft exclude stealth and VSTOL (Vertical/Short Take-Off Landing) airframes.

[11]Such an approach is hardly novel; analysts attempting to reform or improve the U.S. acquisition process routinely study foreign acquisition programs and systems in the hopes of uncovering new approaches relevant to the U.S. situation. Recent examples include U.S. General Accounting Office, 1986; the Center for Strategic and International Studies, Washington, D.C., 1987; and Gansler and Henning, n.d. The RAND Corporation has conducted numerous studies of foreign acquisition practices, as discussed in more detail in Sec. II below.

Fortunately for this research effort, four very large fighter aircraft development or technology demonstration programs were all launched around the same time in the early 1980s: the *Rafale* A in France,[12] the Experimental Aircraft Program (EAP) in the United Kingdom, the *Lavi* in Israel, and the *Gripen* in Sweden.[13] These programs presented an ideal opportunity to poll foreign officials involved in major R&D efforts about their views on prototyping complex new weapon systems. These programs represent starkly contrasting approaches to the concept of prototyping complex fighter/attack aircraft:

- The *Rafale* A and EAP programs reflect a philosophy of building and flight testing basic unequipped airframe prototypes before commitment to FSD and production, reminiscent of the classic austere pre-FSD prototypes advocated by acquisition reformers for decades.
- The *Lavi* and *Gripen* programs dispensed with pre-FSD prototypes; they opted for a total weapon system development concept based on fully missionized engineering test or preproduction prototypes built and tested after the beginning of FSD and manufactured on the assumption that a commitment to production had already been made.[14]

Section II examines the *Rafale* A and EAP, which appear to adhere to the basic tenets of austere prototyping undertaken before FSD as advocated by the Packard Commission. Section III compares these programs with those of the *Lavi* and *Gripen*, structured in accordance

[12]The *Rafale* technology demonstration prototype received its "A" designation only after the definition of the considerably smaller production version, which Dassault labelled *Rafale* D. Unless otherwise noted, the name *Rafale* alone is always used here to refer to the pre-FSD "A" prototype.

[13]See the appendix for brief descriptions of these four programs and the technical characteristics of the aircraft.

[14]Foreign fighter development programs of course are not structured according to DoD Milestone designations that attempt clearly—if somewhat artificially—to separate the pre-FSD concept validation phase (DoD acquisition regulation Milestones 0 to 1) from the FSD phase (acquisition Milestones 1 to 2). In actual practice, however, the distinction between the concept validation/demonstration phases and FSD in foreign programs is generally quite clear and unambiguous. For the purpose of analysis and comparison, we have divided foreign R&D programs as follows: concept validation/demonstration phases may employ prototypes—usually manufactured on soft tooling by engineering divisions rather than production divisions—to proof test technical approaches, gain better assessments of costs, etc. Alternatively, wind tunnel testing, computer simulation, and other sorts of paper studies may be applied alone. But during this phase, there is clearly no commitment to the development of a fully missionized or equipped engineering test article, much less to actual production. Commitment to developing a fully missionized engineering test article with the intention of entering into series production based on that test article is assumed to be the equivalent to the U.S. concept of FSD.

with entirely different concepts in response to what their developers perceive as a fundamentally changed acquisition environment requiring new approaches. Section IV reviews and compares the findings of the previous two sections and makes some observations about the continuing viability of the classic pre-FSD austere prototype acquisition approach.

II. THE RAFALE A AND EAP: RECENT EXAMPLES OF PRE-FSD AUSTERE INCREMENTAL PROTOTYPING

INTRODUCTION

Beginning in the 1950s with the introduction of its *Ouragan* and *Mystère* fighters, and gaining momentum through the 1960s with the spectacular international marketing success of its highly respected *Mirage* III series aircraft, Avions Marcel Dassault-Breguet Aviation steadily built a reputation as one of the Western world's most efficient and successful developers of first-line fighter-attack aircraft.[1] While one after another of Europe's aerospace firms were succumbing to government imposed takeovers and mergers and were forced to seek international collaboration in response to static defense budgets and sky-rocketing development and procurement costs, Dassault remained defiantly—and profitably—independent. Indeed, by the 1970s Dassault remained the only developer of truly all-national world-class fighter-attack aircraft located outside the United States and the Soviet Union.[2]

More than one observer has attributed Dassault's success to the firm's unique and economical approach to R&D, which in turn has become closely identified with a development strategy emphasizing pre-FSD austere prototyping. The most thorough examination of the

[1] In 1972 Avions Marcel Dassault took over and merged with Breguet Aviation. Hereafter the firm is referred to simply as Dassault. For a biography of the firm's founder and a history of the company, see Assouline, 1983. For a more general background on the French aerospace and arms industries, see Carlier, 1979; Noetinger, 1984; and Kolodziej, 1987.

[2] With the Labour Government cancellation of the TSR.2 and several other combat aircraft programs in 1964, the British aerospace industry ceased developing high-performance first-line fighter attack aircraft on a purely national basis (unless one counts the VSTOL *Harrier* under development since the late 1950s or the *Hawk* trainer). For further discussion, see Gardner, 1981; Wood, 1975; and Reed, 1973. Modern Swedish-developed fighters such as the *Viggen* are heavily dependent on foreign-developed subsystems and components. Fighters fielded by the People's Republic of China generally have been copies or developments of Soviet designs. All other fighter aircraft developed after the early 1960s are the product of collaborative ventures such as the British-German-Italian Panavia *Tornado* or the Franco-British SEPECAT *Jaguar* attack aircraft, or can at best be characterized as less capable utility, trainer/light attack, or counter-insurgency aircraft such as the Aermacchi MB339, the Argentine FMA IA-58 *Pucara*, or the Brazilian Embraer *Tucano*.

key elements of Dassault's R&D philosophy appeared in several RAND studies written in the early 1970s by Robert Perry and Arthur Alexander.[3] Perry's studies pinpointed at least four components of Dassault's recipe for R&D success, all usually closely associated:

- incremental, evolutionary design change,
- minimal bureaucracy, reporting and engineering requirements, and government interference,
- "phased acquisition"—clear separation and avoidance of overlap among various phases of the acquisition process, particularly Research, Development, Testing, and Evaluation (RDT&E) and high-rate series production, and
- early hardware testing, and design and system validation, through austere prototyping before FSD and the production decision.

All the concepts, especially the last, are of course very similar to the concept of prototyping advocated in the 1986 Packard Commission findings.

Historically, Dassault's pre-FSD prototype approach has been characterized by austerity. That is, small design teams concentrated on rapid and low-cost development of a basic airframe test vehicle on soft tooling, lacking all but the most essential subsystems. The resulting prototype, by preference, was typically derived directly from previous Dassault designs, representing only a fairly small technological advance. Alternatively, engineers would typically limit a large technological advance to only one aspect of the design, thus reducing overall risk to a minimum. For example, between 1954 and 1970 Dassault developed the *Mirage* series into 24 variants and 41 individual models derived from 19 prototypes. Designers assessed the feasibility of high-risk technological innovations such as VTOL (Vertical Take-Off and Landing) and VG (Variable Geometry) wings in an economical manner and before any production decision by building prototypes based directly on existing *Mirage* models and modifying only the one area being tested. These prototyping efforts were separated temporally, contractually, and financially from FSD. In a like manner, Dassault separated FSD from series production.

Dassault continued this tradition through the 1970s and into the 1980s. The basic configuration of the current top-of-the-line Dassault fighter, the *Mirage* 2000DA/N, remains remarkably similar to the

[3]See especially Perry, 1973. Also see Perry, 1971; Alexander, 1973; The history and general characteristics of European aerospace industries are examined in Lorell, 1980; and Rich et al., 1981.

original *Mirage* III design developed two decades earlier. Yet the net effect of countless subtle aerodynamic and subsystem design changes based on constant prototyping and hardware testing has once again produced a modern fighter that can hold its own against the world's best. Both the *Mirage* F1.C and the *Mirage* 2000DA/N derived from austere company-financed prototype or design concept fall-back efforts that were adopted when the government realized its much more ambitious efforts—the *Mirage* F2 and *Avion de Combat Future* respectively—would be too costly. Likewise, both programs entered a prototype phase early on in development—at least partly financed by Dassault—and before any production commitment.[4] Furthermore, during the 1970s Dassault also continued to experiment with a wide variety of technological innovations employing test beds and prototypes such as the *Mirage* 4000, derived directly from proven production designs.[5]

Yet, as noted earlier, since the publication of the definitive RAND studies on Dassault in the early 1970s, the acquisition environment has changed considerably.[6] Perhaps most striking, the growing cost and complexity of platforms means that aircraft stay in the inventory now far longer than in the 1950s and 1960s, and far fewer major acquisition programs are undertaken, resulting in longer intervals between program starts. Furthermore, aerodynamics, materials, and subsystems—especially avionics—technologies have changed considerably, while powerful computer aided design and development tools have proliferated.

In the eyes of many authoritative acquisition specialists, Dassault has traditionally represented and exhibited the best attributes of the strategy of early, austere pre-FSD airframe prototyping. Further, the classic Dassault approach is similar to the concept of prototyping advocated by the 1986 Packard Commission. For these reasons we turn first to Dassault to determine whether—and, if so, why and how successfully—the firm continues to adhere to its original approach, or some variation of it, in the changed acquisition environment of the late 1980s. At the same time, we note how the firm now views some of the other attributes listed above generally associated with the Dassault prototyping style. Finally, for the sake of comparison and clarification, we examine the development strategy of Dassault's most immediate and direct European competitor, British Aerospace (BAe). This

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[4]Although once approved by the government, the *Mirage* 2000 went directly to FSD without a pre-FSD prototype.

[5]The *Mirage* 4000 is much larger and more capable than the 2000 but of similar configuration.

[6]An excellent overview of these changes can be found in Rich and Dews, 1986.

comparison is particularly useful because the British firm appears to have adopted an approach similar to Dassault's in its current fighter aircraft development efforts.

PROGRAM BACKGROUND

In the early 1980s Dassault and BAe began constructing competing advanced technology demonstrators that in the latter half of the decade entered intensive flight development programs. In most respects both programs exhibit important features associated with Dassault's traditional development strategy of pre-FSD austere incremental prototyping. Both the *Rafale* A and the Experimental Aircraft Program aircraft (EAP) are technology demonstration and concept validation vehicles, the products of very austere development programs undertaken in part with company funds before any commitment to FSD or production.[7] The firms developing these aircraft also had major political-industrial objectives: demonstration of the technological and developmental expertise necessary to win project leadership for the collaborative European Fighter Aircraft program (EFA). Both technology demonstrators were clearly intended to serve as initial pre-FSD prototypes for the EFA program.[8] Figures 1 and 2 show three-view line drawings of these two aircraft.[9]

In the latter half of the 1970s, the British, French, German, and Italian industries initiated discussions aimed at collaboratively designing, developing, and producing Europe's next generation fighter-attack aircraft. In 1979 BAe and Messerschmitt-Bolkow-Blohm (MBB) combined their national design efforts and presented their governments with a joint design proposal for a European Combat Fighter (ECF). Dassault joined the program in 1980, merging its *Avion de Combat Experimental* (ACX) proposal with the Anglo-German ECF, resulting in the slightly changed trinational European Combat Aircraft (ECA) design. The ECA design emerged as a very agile single-seat twin-

[7]As noted earlier, the *Rafale* D is the designation for the production version of the *Rafale* A and will differ considerably from the demonstrator vehicle in size and equipment.

[8]Although the *Rafale* A and EAP are indisputably austere fighter prototypes similar to the YF-16 and YF-17 of the early 1970s, rather than classic technology demonstrators such as the X wing aircraft sponsored by the U.S. Defense Advanced Research Projects Agency (DARPA), both European firms refuse to label their aircraft as prototypes. This is primarily because of government pressure to avoid any illusion of commitment to FSD and procurement. Nonetheless, initial mockups and drawings of EFA and the *Rafale* D closely approximate the physical appearance of EAP and *Rafale* A respectively.

[9]All figures in this report were reproduced by permission of Pilot Press, Ltd.

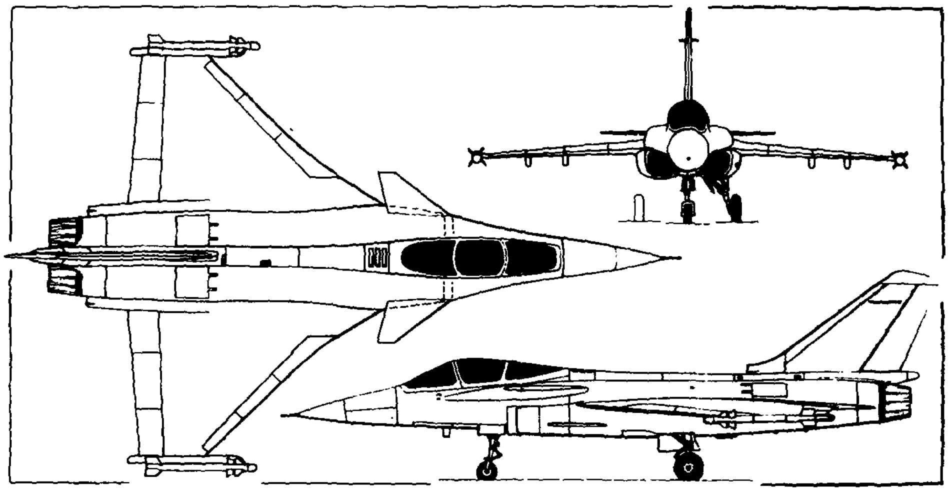

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Fig 1.—Dassault-Breguet Rafale A experimental combat aircraft

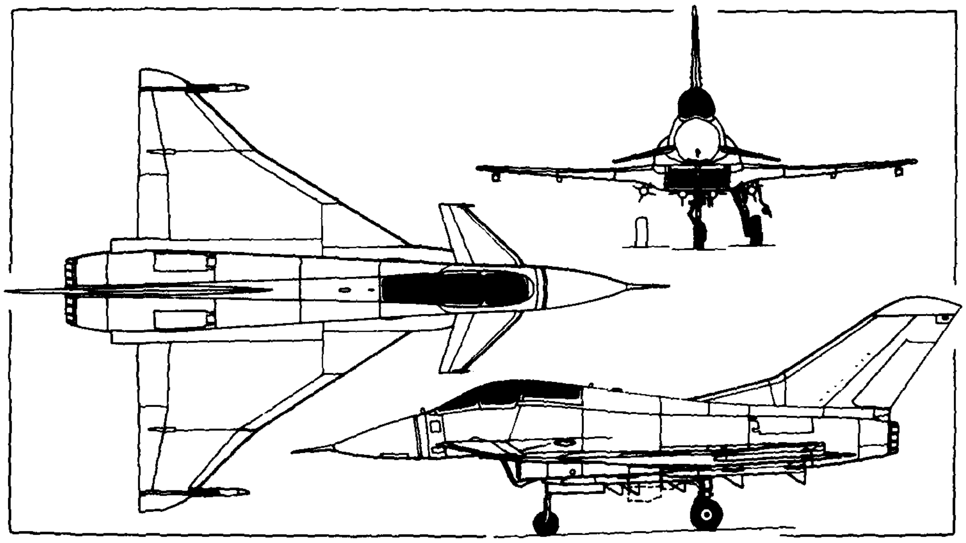

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Fig. 2.—Three-view drawing of BAe EAP demonstrator

engine air superiority fighter with a double-delta wing canard configuration, projected to achieve Initial Operational Capability (IOC) in 1991/92.

Three major problems soon arose that stalled the program. The most important issue involved design leadership and division of responsibility; the French insisted on the need for a clear project leader to avoid rule by committee, with Dassault being the ideal choice,[10] while the others were willing to accept a more egalitarian program structure. The question of design leadership directly affected the second problem area: the aircraft's basic empty weight. Primarily for cost considerations, to facilitate foreign sales, and to meet French Navy requirements for a carrier based fighter, the French preferred a much lighter aircraft than the heavy long-range interceptor envisioned by the RAF. The third problem involved the engine and was also related to questions of size and weight. The *Tornado* partners,[11] spearheaded by the British, pushed for the adoption of a derivative of the *Tornado* RB-199 turbofan engine, whose development Rolls-Royce had dominated. The French preferred a U.S. interim engine for the prototypes, followed by their own SNECMA M88 engine for production models.

Even more important than management and design disputes, the participating governments remained extremely uneasy over the cost and technological uncertainties associated with a program of this magnitude. Given the unhappy experience of massive cost growth combined with schedule and performance shortfalls encountered on the *Tornado* and other European collaborative programs,[12] these governments hesitated to commit themselves to the ECA without a better grasp of the cost implications and technological uncertainties. The ministries of defense were unable to agree on a definitive joint requirement, and with no government funding forthcoming, the ECA project effectively collapsed in 1981.

In response, the lead *Tornado* industrial partners (BAe, MBB, and Aeritalia) continued company-funded design studies on their own initiative in the hopes that government agreement and subsequent funding could be obtained, without France if necessary, after completion of more refined design and cost studies. In April 1982 the three Panavia

[10]Dassault argued that its extensive experience with the delta-canard configuration on such demonstrator prototypes as the *Mirage Milan*, the *Mirage* 4000, and the *Mirage* 3 New Generation uniquely qualified it for project leadership.

[11]Britain, the Federal Republic of Germany (FRG), and Italy collaboratively developed and procured the *Tornado* interdiction/strike fighter in the late 1960s and early 1970s under the auspices of the Panavia and Turbo Union international consortia, the latter for the development of the engine.

[12]See, for example, Lorell, 1980.

companies formally launched a new collaborative design and development effort, excluding direct participation by Dassault. Not surprisingly, the design, called the Agile Combat Aircraft (ACA), closely resembled the proposal advocated by the Panavia and Turbo Union firms during the ECA negotiations. Meanwhile, Dassault forged ahead alone with its own ACX design studies, yet kept the lines of communications open with the Panavia firms. However, fiscal and political realities soon forced the French back in the direction of collaboration. To keep French options open, Dassault developed larger and heavier ACX designs that more closely satisfied British requirements.

But none of the firms could progress very far beyond paper studies without government funding. Indeed, British industry had already expended some £25 million of company funds just to support its ACA-related design studies. Yet given worsening budget constraints and past experience with cost overruns, none of the participating governments was about to commit to a potentially ruinously expensive FSD program on the basis of computer simulations, paper studies, and promises, particularly when neither the firms nor the governments could agree on a European joint requirement and the industrial division of labor.

CONTRACTUAL, FINANCIAL, AND MANAGEMENT ARRANGEMENTS

The immediate solution to this dilemma was found in the partial funding of two technology demonstrators. In effect, the solution adopted amounted to the de facto competitive national development of two prototypes before collaborative FSD to reduce technological and cost uncertainties and to aid in the selection of the final design, configuration, and lead contractor. In September 1982, the British Ministry of Defense (MOD) announced that it would provide partial funding for the development of an experimental technology demonstrator, although a formal contract was not signed until May of the following year. French Minister of Defense Charles Hernu gave the final go-ahead to Dassault for the development of the ACX technology demonstrator in April 1983. Some months earlier the Defense Ministers of France, Britain, and the FRG had formally agreed to again begin negotiations for a joint requirement for the collaborative development of a Future European Fighter Aircraft (FEFA), later re-designated European Fighter Aircraft (EFA).[13]

[13]The first designation was dropped when an alert linguist pointed o. t that the acronym FEFA was an obscene term in Italian, or so it is claimed.

Government negotiators on both sides of the Channel made sure that the EAP and ACX development contracts minimized governmental obligation (and interference) and maximized industrial risk-sharing, while providing support and incentives to the chosen national instrument in its quest for EFA project leadership. The participating governments made no FSD or production commitments of any kind.

The British MOD contract with BAe stipulated the collaborative development of one test vehicle, later dubbed the EAP, to be completed in no more than three years, for which the government would pay half of BAe's projected development costs—£65 million—on a fixed price basis.[14] This arrangement placed at least half of the demonstrator development cost and, since it was a fixed price contract, most of the risk on industry. Payments would be made when the contractor met designated milestones. However, the contract stipulated very few reporting requirements; no detailed performance or technical specifications were identified. Furthermore, BAe had virtually a free hand in organizing and managing the project. No MOD research experts would be involved unless specifically requested. Upon completion of the test vehicle, which would remain under industry ownership, the contract would terminate. No funds were included in the original contract to support a flight test program, thus further reducing government obligation and commitment.

In most important respects the French government contract with Dassault duplicated the EAP contract, with the exception that the effort was purely national from its inception. Dassault agreed to develop one technology demonstrator based on its ACX design, with a first flight no later than the end of 1986; the government and the firm would each pay one-half of the development costs. A one-year flight-test program was initially envisioned.

Clearly the BAe/MBB/Aeritalia and Dassault teams hoped that their respective demonstrators would eventually be selected as the prototype for full-scale development of the EFA. There is no doubt that, at an absolute minimum, they hoped and expected to receive further funding to support flight testing once the demonstrators were

[14]Originally, MBB and Aeritalia had planned to collaborate on the program with German and Italian government financial support. Indeed, MBB had expected to manufacture a second technology demonstrator prototype in the FRG. Some months after the commencement of the collaborative program, however, both the FRG and Italian governments withdrew financial support from the ACA to appear more impartial in the ongoing negotiations over EFA project leadership. As a result, British government funding increased to £80 million in accordance with a contingency clause in the contract designed to compensate BAe in the event of the withdrawal of a foreign partner. BAe redesignated the now purely national project EAP and continued to develop the demonstrator based on its original ACA studies. Aeritalia continued to participate in the project on a commercial contract basis by utilizing its own company funds.

completed. For a variety of domestic political, economic, and technological reasons, the French and British governments had to provide some support to the R&D efforts of their national aerospace industries. But at the same time, they endeavored to reduce their financial risk and commitment as much as possible to retain maximum flexibility in negotiating a broader European-wide EFA agreement. Such an agreement might require sacrificing important aspects of the approach selected by each nation's prime aerospace contractor, for the sake of attaining European political/industrial objectives and budgetary economies through collaboration.

It was primarily for these reasons that the British and French governments continually stressed—and demanded their industries confirm—that the EAP and the ACX were purely and exclusively technology demonstrators intended neither to serve as prototypes for the EFA nor as a precursor to purely national FSD programs. Few observers, however, believed these protestations from industry. To emphasize their determination, both the French and British governments resisted industry pressure to fund flight test programs once the demonstrators were completed, causing at times considerable strain between government and industry, particularly between Dassault and French Minister of Defense Andre Giraud.

In the case of the EAP, the original development contract had contained provisional clauses regarding the financing of a flight test program. But on completion of the test vehicle, the MOD declined to finance one because of the withdrawal of the other international partners. Furthermore, France had effectively dropped out of the EFA negotiations during the summer of 1985.[15] Nonetheless, BAe commenced flight testing of the EAP in August of the following year, financed primarily with corporate monies. The British firm undertook this test program with the understanding—or at least the hope—that Eurofighter[16] would eventually reimburse it if the remaining participating governments approved full-scale development of the EFA based on the EAP.

Dassault's ACX, christened the *Rafale*, first flew a little over a month before the EAP—on July 4, 1986—a mere 27 months after the beginning of serious development work.[17] Dassault launched a vigorous

[15]Conventional wisdom suggests that Dassault's dislike and distrust of collaborative programs, combined with concern about the growing size and cost of the EFA design, led to French withdrawal.

[16]The international consortium established by Britain, the FRG, Italy, and Spain in June 1986 to develop EFA.

[17]The demonstrator *Rafale* prototype received its "A" designation only after the definition of the production *Rafale* D version.

flight test program—financed in part from corporate funds—that substantially exceeded 100 sorties in the first 12 months. At the same time, the firm lobbied intensely for government funding for FSD, but it was not immediately forthcoming.

Consistent with the basic principles of austere pre-FSD prototyping, the partial government funding of the *Rafale* A and EAP demonstrator programs reflected no definite commitment to FSD by the sponsoring governments. This is made abundantly clear by the considerable difficulties and delays the developers encountered during their battles to win approval for FSD.

Even before Dassault pulled out of EFA, the firm had begun an intensive lobbying effort for a FSD contract for a national fighter based directly on a scaled down version of the *Rafale*. The larger *Rafale*, designated "A," was sized to meet the EFA requirement. The scaled-down production version intended for the French Air Force, called *Rafale* D, is slightly smaller and about 2000 lb lighter empty but of identical shape and configuration.

After a long and sometimes acrimonious battle, Defense Minister Giraud finally approved FSD in principle of the *Rafale* D in mid 1987. At the end of the year, a special ministerial committee formally approved FSD, expecting the signing of contracts with Dassault and SNECMA in the spring. Finally, in April 1988, the Minister of Defense signed an initial contract covering only the first two *Rafale* D FSD prototypes (out of the projected five) and requiring extensive funding contributions from industry. At that time government financial support of the *Rafale* A flight-test program ceased.

The FSD decision for the EFA also did not come soon or easily, primarily because of German concerns over mounting projected development costs. Britain, Germany, and Italy finally signed a Memorandum of Understanding (MoU) on May 16, 1988 formally authorizing full-scale development of EFA, but Spain's future involvement in the program remained uncertain, casting continued doubts on the viability of the FSD program. Because of huge unexpected FSD costs and growing budget constraints, the EFA and *Rafale* D projects remained extremely controversial. Both the EFA partners and the French continued to woo Spain throughout the summer of 1988, hoping to convince her to join their projects in the interest of spreading FSD costs among more partners. On November 9, 1988, the Spanish government opted to join Eurofighter and signed the EFA MoU. Since then the *Rafale* D FSD program has come under increasing criticism in France as too expensive for a single European country to pursue alone.

Whether these two FSD programs will be pursued to completion remains to be seen, given the high costs associated with FSD.

Nonetheless, it is now possible to make some initial assessments and observations regarding the utility of the pre-FSD austere prototype phases of the two programs.

TEST OBJECTIVES FOR A MODERN PRE-FSD AUSTERE PROTOTYPE

With fixed price government contracts providing only half the projected development funding, no guaranteed financial support for flight testing (in the case of the EAP) and absolutely no commitment to FSD—much less production—both the EAP and the *Rafale* A can accurately be described as austere pre-FSD prototype programs. Neither aircraft is equipped with any missionized equipment or avionics, such as a central mission computer, electronic warfare suites, or radar. Both aircraft were intended only to demonstrate and validate certain new technology applications and design concepts primarily related to the airframe and flight control systems.

Despite persistent assertions to the contrary by the sponsoring governments, few observers believe that the developers of these test aircraft intended them to represent anything other than the pre-FSD prototype 01 of the EFA program or of a national fighter full-scale development effort. Clearly both contractors desired to demonstrate technological virtuosity in hopes of winning EFA, or possibly even national project leadership. It is thus legitimate to raise the question of whether these programs were largely political in nature, in that their primary purpose may not have been related to improving acquisition efficiency. Yet now that FSD has been authorized, their developers view these technology demonstrators as having served an important developmental function in testing uncertain technologies and concepts, thus reducing risks and permitting more informed FSD technological decisions and program planning.

Both BAe and Dassault assigned similar technological test objectives to their pre-FSD prototypes, concentrating on the following areas:

- Unstable aerodynamic designs and active flight control technologies;
- Advanced structures and materials;
- Advanced cockpit design, information displays, and pilot ergonomics.

The question of interest here is whether the early demonstration of these technologies on austere prototypes reduced technological, design, fabrication, or production uncertainties to an extent that benefits during FSD in terms of more informed technological and design expectations and tradeoffs will exceed any additional costs associated with the early prototype effort. At this early stage in the development cycle, of course, it is difficult even to venture tentative answers to these questions.

Yet in the view of the EAP and *Rafale* program managers we queried, the benefits of early pre-FSD airframe prototyping clearly exceed the costs. Particularly in the area of aerodynamic design and flight control systems, both contractors believe the test information generated by their prototypes will substantially improve the efficiency of the FSD programs by reducing the size of the jump in some of the key technology applications required to develop the next generation fighter weapon system.

Aerodynamics and Flight Control Systems

Dassault especially desired to use its pre-FSD *Rafale* A prototype to continue its traditional approach of reducing risk through incrementally improving and refining the delta wing/canard configuration, an aerodynamic design with which it had substantial experience. The French firm had begun experimenting with a movable foreplane to overcome the shortcomings of the delta wing with its *Mirage*-derived *Milan* test vehicle in 1969, progressing to a variable incidence foreplane on the *Mirage* 4000 prototype of the late 1970s and early 1980s. With the *Mirage* 2000, equipped with a stubby fixed canard, Dassault took its first steps toward an aerodynamically unstable design on a production aircraft, devising an analog Fly-By-Wire (FBW) system for flight control. *Rafale* A is a more unstable design—a genuine control configured vehicle (CCV)—employing more control surfaces, including an all-movable canard. To manage this more challenging design, engineers developed Dassault's first fully numerically controlled quadriplexed digital FBW flight control system.[18] These features, along with other aerodynamic design approaches new to Dassault, such as the nonmovable side-angled air inlets, were proof-tested and fine-tuned on the *Rafale* A.

The British approach duplicated much that was going on at Dassault. In particular, program officials emphasized development of an advanced FBW system by GEC Avionics for the EAP derived from

[18]The General Dynamics F-16A/B is equipped with an analog FBW control system of the sort developed later for the *Mirage* 2000. The McDonnell Douglas/Northrop F-18 was the first fighter to fly with a digital FBW system. Lear-Siegler developed a digital FBW control system for the F-16 in the early 1980s, at about the same time that the British firm GEC was developing and equipping a prototype digital FBW system on a BAe *Jaguar* testbed, somewhat ahead of Dassault's efforts in this area.

experience gained with the *Jaguar* testbed experimental digital FBW system.

Both technology demonstrators permitted engineers to experiment with risky, advanced unstable aerodynamic designs characterized by double delta wing configurations combined with all-movable canards, intended to maximize agility. Furthermore, fully digital quadriplexed FBW flight control systems without mechanical backup, operating as many as 17 movable control surfaces in the case of the *Rafale* A, could be fully proof tested without fear of compromising a costly FSD program. Indeed, Dassault engineers claim that substantial modifications and refinement of flight control software resulted from the flight testing of the prototype. These changes are expected to contribute substantially to the efficiency of the FSD program. Furthermore, these are precisely the areas where the Israelis and Swedes have experienced some of their most serious development problems in their fighter FSD programs.[19]

Advanced Structures and Materials

According to their developers, both prototype demonstrators have clearly made a major contribution to a better understanding of the use, fabrication, and production of major airframe structures formed from exotic materials. Here again, both contractors have adopted an incremental approach, using the *Rafale* A and EAP demonstrators as a major step in the development evolution of these technologies. About 25 percent of the structural weight of both prototypes is manufactured from composite materials, mostly carbon fiber composites (CFC), but also some Kevlar. Before the current programs, BAe and Dassault had extensive experience producing small airframe parts such as control surfaces and panel doors from CFC, but both hoped to make much more extensive use of CFC and other exotic materials on their next generation fighters.

As a first step, both firms developed test articles, prototypes, or simpler versions of large difficult fuselage structures, such as all-CFC bonded wings. For example, Dassault drew heavily on the experience gained from the V10 wing developed for the *Falcon* jet, as BAe did from the modified *Jaguar* and the *Harrier* wing development. The *Rafale* A wing itself underwent extensive ground testing at the Toulouse Test Center before attachment to a static test vehicle for further design verification. As the next step, the *Rafale* A and EAP serve as a transition stage between CFC prototype structures and

[19]See Sec. III.

production aircraft using composite and exotic materials for much of the airframe.

Besides CFC, both firms experimented extensively with other exotic materials and processes such as Super Plastic Formed/Diffusion Bonded (SPF/DB) titanium and aluminum-lithium alloys for structures with complex shapes such as the *Rafale* A's main wing leading edge slat sections.

Dassault's managers argue that particularly in this area of advanced materials, austere prototypes like the *Rafale* A permit extremely beneficial experimentation. After manufacturing and flight testing the prototype, much more informed choices can be made regarding tradeoffs of potential performance gains against cost and producibility. Dassault engineers insist that the information gathered in this area from their early prototype testing far exceeded anything attainable from paper studies or simulations and has substantially reduced risk and uncertainty in the use of such structures in FSD and production articles.

Cockpit Design and Information Display

Finally, designers and engineers at BAe and Dassault have also experimented considerably with advanced cockpit design, information displays, and pilot ergonomics on their technology demonstrator prototypes. For the *Rafale* A, specific features include seat inclination up to 50 degrees, side stick and throttle, voice dialog alarm system, and task-oriented display of information on a wide-angle Head Up Display (HUD), a head-level color display, and two color Cathode Ray Tube (CRT) and one liquid crystal display in the cockpit. The EAP cockpit boasts many similar features and innovations.

According to company officials, Dassault would not have attempted to incorporate many of the *Rafale* A's advanced cockpit features on a FSD prototype or test vehicle. Here again, the risks of failure were perceived as being much lower on a technology demonstrator pre-FSD prototype, permitting experimentation with innovations of uncertain advantage or cost-effectiveness (from Dassault's point of view and experience). One example of such a feature was the extreme inclination of the pilot's seat. Using a flying prototype for concept validation also contributed to the development of the information visualization features such as symbology and layout of screens and HUD.

SUMMARY OBSERVATIONS

Both the *Rafale* A and EAP, although labeled purely as technology demonstrators for political reasons, closely resemble traditional incremental, austere early pre-FSD prototype programs. They were financed by fixed-price government contracts providing only half the projected development funding. The sponsoring governments provided no guaranteed financial support for flight testing (in the case of the EAP) and absolutely no commitment to FSD, much less production. Both aircraft were financed on a shoestring—the total cost of the EAP was a mere £180 million—and had no major subsystems, avionics, and weapon systems. Indeed, neither prototype is equipped with any major subsystems—other than the flight control system and man-machine cockpit interfaces—intended for use on the fully missionized and developed weapon system. This is even true of the engines. The *Rafale* A is powered by a completely different engine—the GE F404—than the SNECMA M88 in development for the production version. To economize, major parts of the rear fuselage and vertical stabilizer of the EAP are borrowed directly from the *Tornado* currently in series production, as are the engines that power the test aircraft.

Furthermore, both prototypes benefited from incremental development of key technologies on earlier test-beds or prototypes. Small design teams with little government oversight or interference were permitted wide latitude to experiment with creative technical solutions, without the restrictions of detailed government specifications. In short, these two aircraft are indeed the modern corollaries of the austere incremental airframe prototypes of the 1950s. And as development projects, these two programs clearly benefited from this approach: Both aircraft first flew nearly six months ahead of schedule, and met or surpassed performance and cost expectations.

Yet do such prototypes contribute measurably to enhancing the efficiency of FSD programs given the vastly changed acquisition and technological environment of the late 1980s? The developers of the *Rafale* and EAP respond with a resounding "yes". Dassault and EAP managers argue with conviction that these test vehicles

- provided unique opportunities to experiment with technologies, applications, and concepts that would have been forgone on a FSD prototype because the risk would have been too great, and
- permitted proof-testing and refinement of complex technological issues in a much more informal and lower-cost environment, allowing a much greater level of confidence to be reached for estimates of FSD costs and technological risk.

These advantages, program managers argued, applied especially to the areas of aerodynamic configuration and flight control systems, exotic and advanced materials and structures, and cockpit design and pilot ergonomics. Other areas not previously mentioned also benefited: digital engine control, radar absorbing materials, and data bus development to name a few.

It is much too early to assess the magnitude or relative importance of these alleged benefits. Both *Rafale* and EFA have only recently entered into FSD as of this writing (spring 1989). Projections for FSD call for the manufacture of five to eight engineering test vehicles. Among other things, these aircraft will act as testbeds for the extremely demanding and costly task of developing and integrating the myriad subsystems and avionics into an effective missionized weapon system.[20] Given the enormous increase in the cost, complexity, and importance of subsystems—especially avionics—relative to the air vehicle, it is not clear how much leverage overall is actually still gained through a classical strategy of early austere airframe prototyping. Is it not indeed a luxury that can be dispensed with in certain circumstances, particularly in light of the sophisticated computer design and simulation now available to airframe designers? The program managers of the *Rafale* and EAP think not, but their views are difficult to assess objectively.

Yet it is possible to make some rough comparisons and contrasts to two other foreign fighter development programs currently or recently in progress that have opted for an entirely different development philosophy and strategy. These two programs, of course, are the Saab-Scania *Gripen* and the Israel Aircraft Industry (IAI) *Lavi*. Questioning the developers of these two aircraft, and carefully examining program structures and objectives, made it possible to gain further insight into the usefulness of the classical approach of pre-FSD austere airframe prototypes.

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[20]In spring 1989, the French awarded a 2 billion franc ($317 million) radar FSD contract for *Rafale* to Thomson-CSF and Electronique Serge Dassault. It includes an unspecified number of prototypes but no production articles. Flight test of the SNECMA M88 turbofan on the *Rafale* has only recently begun. Neither the production standard engine nor the radar has been selected for EFA.

III. THE LAVI AND GRIPEN: THE CASE FOR THE FSD MISSIONIZED TEST VEHICLE

INTRODUCTION

The IAI *Lavi* and Saab-Scania JAS 39 *Gripen*[1] are in physical appearance and configuration similar to the *Rafale* and EAP, as shown in Figs. 3 and 4 and in the appendix. Yet the Israeli and Swedish programs are in many respects examples of a development approach fundamentally at odds with the precepts of early austere prototyping and associated concepts as outlined in Sec. II; indeed, they are much more akin to the U.S. total system acquisition style of the McNamara years in the early 1960s applied to such programs as the General Dynamics F-111A.[2]

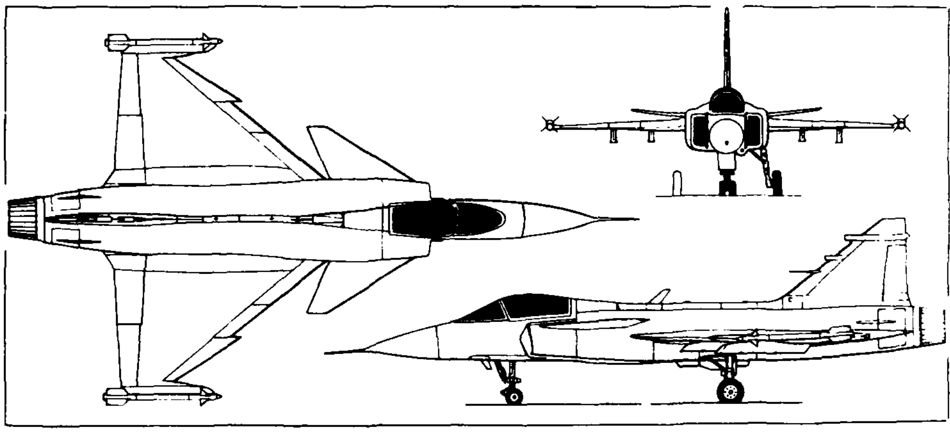

Fig. 3.—Saab JAS Gripen multi-role combat aircraft for the Swedish Air Force

[1]JAS is a Swedish acronym for Fighter (*Jakt*), Attack (*Attack*), and Reconnaissance (*Spaning*).

[2]See Coulam, 1977.

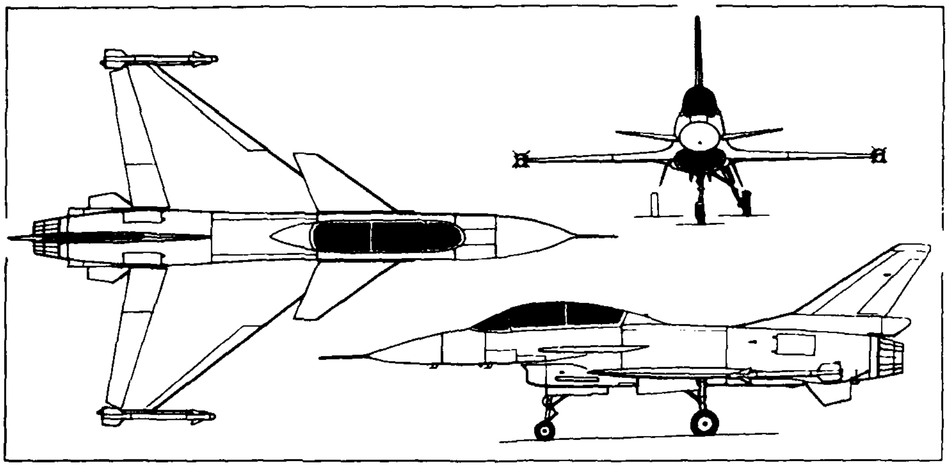

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Fig. 4.—IAI Lavi close support, strike and air defense fighter

Construction and testing of an austere airframe prototype like the *Rafale* A or EAP before the decision to proceed with FSD and series production was rejected in Israel and Sweden for several reasons. In both countries such an approach was associated with unacceptable political, industrial, and financial costs. Furthermore, development officials argue that the changed technological environment of the late 1980s not only reduces the benefits of the austere prototype but actually requires the entirely different approach of total system development.

On the negative side of the ledger, officials in both countries insist that austere airframe prototyping is an unnecessary luxury that only rich countries can afford. This is particularly true, it is argued, for small countries that for political reasons have few realistic prospects of collaboration or foreign sales. Confronted with the likelihood of small production runs, the cost of prototyping before FSD looms much larger relative to total program costs.

Great concern is expressed in Sweden and Israel regarding the political, industrial, and military risks associated with delaying a decision on FSD and production pending the completion of an austere prototype test program. In both countries, national development of advanced fighter aircraft has become a highly politicized issue with enormous industrial and economic ramifications. Supporters of such programs in industry and government push hard for early FSD and production decisions to commit hesitant parliaments beyond the point of no return.[3] These advocates believe that early demonstration prototyping makes programs too vulnerable to cancellation, a disastrous outcome in countries with only one set of aerospace contractors and one program. In the case of the *Lavi* and *Gripen*, the debate over whether to proceed at all dragged on for so long that any further delay in FSD would have risked major layoffs in the production divisions of the prime contractors. Existing production programs, the *Kfir* C2/7 in Israel and JAS 37 *Viggen* in Sweden were rapidly approaching completion. Circles within the Israeli military also pushed for early FSD because of the view that for a country perpetually on the verge of hostilities, it is better to field an imperfect system quickly so that it is at least available for combat if needed. According to this view, in situations where war can be expected to break out any time, it is preferable to have "rubber on the ramp" with only 80 percent of the expected capability than no new aircraft at all. The unstated assumption is that pre-FSD prototyping leads to longer overall development programs, something that is far from certain, at least in the U.S. context.[4]

On the positive side of the ledger, officials in both countries insist that technology trends have rendered austere airframe prototyping unnecessary, while requiring a return to a system approach with fully missionized prototypes. According to this line of argument, things have changed fundamentally from the early 1950s, or even the early 1970s, when airframe and engine technologies were advancing rapidly, while most subsystems played a fairly simple and small role in the overall development effort. In earlier years, the greatest developmental effort—and the largest technological risk. and uncertainties—were associated with the air vehicle itself. Thus, in a period of rapid technology advance in aerodynamics, early austere airframe prototyping represented a high-leverage approach to risk reduction.

By the late 1980s, so it is argued, technology trends have transformed the basic airframe/engine combination into a low risk part of the development program. With reduced emphasis on achieving ever higher speeds and altitudes, the emphasis on pushing aerodynamic development to the limit has declined.[5] Finally, the introduction of more sophisticated wind-tunnel testing techniques, combined with powerful new computer simulation tools and CAD/CAM, permit

[3]In Europe and Israel a decision to proceed with FSD is almost always perceived as an irreversible commitment to production.

[4]See Smith et al., 1981; and Smith and Friedmann, 1980.

[5]Some observers believe this argument must be heavily qualified to exclude the development of stealth and VSTOL (Vertical/Short Take-Off and Landing) technologies.

extremely accurate and detailed refinement of designs before hardware development, thus minimizing the need to proof-test aerodynamics with austere airframe prototypes.

Instead, avionics—especially avionics integration—are viewed as being the highest risk, highest uncertainty component of modern fighter R&D efforts. Avionics development—especially radar, weapons management, EW (Electronic Warfare), navigation, and flight control systems—now can represent 50 percent or more of development costs. Further, avionics are now often conceived as parts of a unified system employing standard computers and languages linked by data bus. In this view, avionics must be developed together and integrated as a single complex system. It is particularly in the area of avionics integration and software development that the perceived development risks are so high.

Two hardware development tools are advocated to increase acquisition efficiency in the high risk area of avionics. One is the establishment of advanced ground-based avionics simulation and test laboratories for development of hardware and software. These labs can be used to optimize man-machine interfaces and begin the process of avionics integration. In this view, however, the bulk of the integration work has to be accomplished on a fully missionized prototype; in other words, on fully equipped FSD engineering test articles configured as close as possible to the anticipated production version. Some observers argue that avionics development and integration cannot be fully accomplished without the assistance of a prototype that is actually operated as a production item by typical operational units in the field. Austere airframe prototypes are thus seen as an anachronism; they contribute little or nothing to reduction of uncertainty where it counts, in high-risk avionics development and integration.

In this view, the development of a useful prototype is almost equivalent to entering into FSD. Consequently, it is also difficult to retain several of the other important features often associated with a strategy of early austere prototyping, particularly as originally practiced by Dassault. The new approach is unlikely to be austere in the sense of the low-cost efforts supported by small development teams, and only lightly burdened with minimal specifications, bureaucracy, and government interference as advocated by Dassault. The total system approach thought necessary by some requires the sort of large-scale expensive programs that governments often feel obligated to monitor and control closely.

Finally, it is claimed that in today's changed acquisition environment it is impractical to adopt an airframe prototype approach based on incremental, evolutionary design change, for the simple reason that the huge growth in development costs has greatly diminished the number of new starts. New designs can be based less on small design improvements, because each one must reflect the decade or more of changes in mission requirements and technology since its predecessor design was fielded. As a result, some believe that modern fighter designs can be generated only by large teams of engineers conducting years of expensive and complex computer simulations and design studies.

The *Lavi* and *Gripen* serve as interesting—although imperfect—test cases for many aspects of this development philosophy. Both programs were clearly laid out in accordance with principles of the missionized FSD approach. Nothing more than very tentative subjective assessments of both programs can be proffered, however. The Israeli government cancelled the *Lavi* project halfway through development after a rancorous public debate and the application of enormous political pressure from the U.S. government, the source of most of the funding for the project. While still underway, the *Gripen* program is as of the spring of 1989 in an early stage of development and remains an extremely sensitive politicized program in Sweden. In such an overheated atmosphere, it is difficult to obtain unbiased insights or objective data. Nonetheless, information is available sufficient for making tentative assessments, particularly compared with the *Rafale* A and EAP programs.

PROGRAM BACKGROUND

Both the *Lavi* and *Gripen* entered into FSD in 1982 after nearly a decade of paper studies, simulations, wind-tunnel tests, and incredibly complex industry-government negotiations. A brief recounting of the background of these two programs is necessary to shed light on the development strategies eventually adopted.

In the mid-1970s Israeli industry launched a conceptual study phase for the development of a large F-18 class fighter equipped with two GE F-404 engines and dubbed the *Aryeh*. Between 1975 and 1977 IAI spent somewhere between \$30 and \$50 million on concept and design studies. In early 1978, following the election of a new government, the new defense minister Ezer Weizmann reexamined the *Aryeh* concept, ultimately rejecting it as too costly. IAI replaced it with a lower-cost single engine design equipped with the GE 404 turbofan.

In February 1980, the Israeli Cabinet gave formal approval to the MOD for the commencement of a wide-ranging concept development phase for the new fighter, characterized by Israeli MOD officials as equivalent to the U.S. concept validation phase (DOD milestone 0 through 1). The objective was to resolve all issues regarding design, configuration, and technologies, based on a detailed assessment of the threat, computer simulation of future air combat, and extensive development, procurement, and life-cycle cost estimating. A key decision came in May 1981, when the Cabinet decided that if a fighter was to be developed entirely in Israel, then new, more stringent Israeli Air Force (IAF) requirements would have to be met to justify the effort. These new requirements resulted from simulation studies indicating that higher speed of low-level penetration was required to guarantee adequate survivability on attack missions. The proposed fighter therefore had to be equipped with the more powerful Pratt & Whitney 1120 engine, rather than the GE 404, making it considerably heavier and more expensive than the scaled-down *Aryeh* proposal. Two more years of paper studies and simulations were undertaken to refine the requirements and the final design concept before the Cabinet gave the final go-ahead for FSD. Although IAI signed the FSD contract in July 1982, the Lebanon War and the need to acquire special supplementary Foreign Military Sales (FMS) funding from the U.S. Congress delayed the commencement of the full-scale development phase another year.

The background of the *Gripen* program in many respects is remarkably similar. The Swedish Air Force (SAF) initiated concept studies for the replacement of the *Viggen* as early as 1971. In 1975, more detailed studies were launched by the SAF, industry, and the civilian acquisition authority, the Defense Materiel Agency (FMV). In response to several changes in government, and growing concern about escalating R&D costs, Saab scaled down the proposed fighter through several iterations from a high-performance *Viggen* replacement to a light trainer/attack aircraft designated the B3LA, and later the A38 and SK2, even cheaper and less capable variations. The crucial turning point in the program came in the fall of 1979, when additional SAF simulation studies convinced the newly elected conservative government that a much more capable aircraft than the SK2 had to be procured. Industry reinforced this conviction by arguing that, based on its studies of new technological developments, particularly in the areas of advanced materials and electronics, a fighter as capable as the *Viggen* or more capable could be developed at one-half the weight and one-half the cost. Furthermore, industry contended that with advanced electronics, one version, equipped with the same internal subsystems, could be developed to effectively perform all the missions of interception, ground-attack, and reconnaissance that required three distinct and very different types for the *Viggen*.

While remaining somewhat sceptical, the Swedish government agreed in June of 1980 to fund a two-year concept development and study phase. Government officials directed industry to form a single consortium, designated Industry Group JAS (IG JAS), to develop a final design proposal and to provide a single partner for contract negotiations.[6] During the first year, industry completed its JAS 39 design proposal, and the FMV conducted extensive cost analysis and simulation studies. IG JAS submitted its final proposal to FMV for evaluation in June 1981. The second year witnessed intensive and difficult negotiations between IG JAS and the government for a FSD contract.

As in the case of the *Lavi* program, neither industry nor government in Sweden ever seriously considered establishing a hardware test phase before a final FSD decision for evaluation of a technology demonstrator or an austere airframe prototype. In both cases, only computer simulations and paper studies were conducted. From the industry perspective, IG JAS was fighting for the very survival of an independent broad-based military aerospace sector in Sweden. Only by unequivocally committing the government to FSD and production of the JAS 39 could survival be guaranteed. Furthermore, program launch had already been delayed for years by parliamentary indecision and leftwing opposition; most program advocates believed that FSD had to begin as soon as possible not only to retain some chance of still meeting the SAF's modernization timetable, but also to guarantee a smooth transition in production from the *Viggen* to the *Gripen* without gaps and layoffs. All these considerations applied more or less equally to the *Lavi* program. But in the hope of avoiding unpleasant surprises, the Swedish government went far beyond the Israeli government with respect to the development contract: the Swedish govenment insisted that industry precisely spell out the terms of—and formally guarantee—every aspect of the development and production program from the outset of the project, in the mistaken belief that uncertainties and unwelcome program outcomes could be avoided or reduced by placing most of the risk on industry.

FSD contracts for both the *Lavi* and *Gripen* emerged directly out of concept validation phases based largely on simulations and paper studies. These two contracts differed considerably, however; some of those differences appear to have substantially affected the course of the FSD programs.

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[6]The IG JAS is made up of the four most important companies developing the *Gripen*, all of which are privately owned: Saab-Scania Aircraft Division, Volvo-Flygmotor (for co-production of the uprated GE 404 turbofan designated the RM12), Ericsson Electronics for the radar and EW, and FFV (*Forenade Fabriksverken*) for ground support and maintenance.

CONTRACTUAL, FINANCIAL, AND MANAGEMENT ARRANGEMENTS

To avoid an open-ended financial commitment to new fighter development programs of uncertain merit and substantial technological and military uncertainty, the British and French governments supported a strategy of program incrementalism and pre-FSD austere prototyping. These governments agreed only to fund single technology demonstrators, thus delaying any decision on FSD until collaborative and other options could be fully explored. The Israelis and Swedes jumped from paper studies and computer simulations directly into FSD. Industry and government officials believed that the basic airframe development effort would be low to moderate risk, not justifying the added expense and time of a pre-FSD prototype.

The Swedish government, however, attempted to adopt a much more comprehensive contractual strategy intended to limit and control government commitment and risk. The Israelis were more relaxed about the nature of the FSD contract, in part because they had succeeded in obtaining massive U.S. Foreign Military Sales funding for R&D. A fairly standard document, the *Lavi* contract included a target cost plus an uncertainty escalator for R&D, and a fixed price for the production phase. The Swedish government, however, having no such generous outside benefactor, attempted to transfer as much monetary and technological risk to industry as possible through a fixed price contract with rigid performance and schedule guarantees. The government was determined to avoid the sort of cost growth and performance shortfalls experienced on the cost-plus contract on the *Viggen* program. The contract negotiated for the *Gripen* program thus violates many precepts often associated with the Dassault austere prototype approach, including emphasis on mission rather than performance requirements, and minimal government involvement and reporting requirements. The nature of the *Gripen* R&D effort cannot be fully grasped without a brief discussion of this remarkable contract.

The *Gripen* contract signed by IG JAS is in many respects unprecedented in aerospace R&D history. Industry hoped to win a target price FSD contract with performance incentives, but the political situation during the contract negotiations heavily favored the government.[7] The

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[7]Parliamentary elections loomed in the early fall during the final contract negotiations taking place in the spring of 1982. As the main opposition party, Palme's Social Democrats generally opposed the JAS 39 program, placing great pressure on the government to negotiate a favorable contract with industry. Even after the signing of such a contract in June 1982, the Social Democrats did not support program approval; furthermore, leading Social Democrats threatened to review the official approval of FSD if the party won the election in September. The Social Democrats indeed came to power as a result of these elections, and did review the IG JAS contract, but did not alter it.

final document signed at the end of June 1982 is a true total-package life-cycle cost contract, consisting of two essential parts. The first part contains a fixed-price contract for the design, development, and testing of five FSD test articles, plus the manufacture of the first 30 production aircraft, including all spares, test equipment, and documentation.

The five developmental prototypes are full-scale engineering test articles. As was originally the case in the *Lavi* program, the first two prototypes are intended to test the basic air vehicle flight characteristics, flight control system, and airframe-engine combination. Prototypes three through five are planned to be fully missionized preproduction test articles equipped with all critical avionics and internal subsystems of the production weapon system. All prototypes, *including the first*, are manufactured at least in part on hard tooling.[8]

The second part of the contract specifies "not-to-exceed" ceiling prices for each block of the next 110 production aircraft, based on an estimate of the learning curve effect and the fixed average fly-away price of the first 30 production aircraft. This part of the contract also includes development and procurement of all external munitions, reconnaissance, and EW equipment.

The total value of both parts of the contract is 37 billion 1982 Swedish Kroner (SEK), or about 6–7 billion 1987 dollars.[9] The fixed price contract applies to a full 13-year FSD and production schedule,[10] during which time there is little available contingency funding or other provision for unforeseen technological problems or uncertainties. Early on the "not-to-exceed" ceiling prices negotiated for the production contract came to be viewed by industry representatives as totally inadequate for recovering a reasonable percentage of any unexpected costs arising during the fixed-price R&D phase.

The IG JAS contract contains strict schedule requirements and warranties, in both mission performance and reliability,[11] including

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[8]Saab-Scania makes the unlikely argument that composite manufacturing technology makes the use of hard tooling from the beginning necessary. However IAI manufactured much of *Lavi* prototypes 01 and 02 on soft tooling. Nonetheless, major airframe segments of the *Lavi* such as the tail were constructed by IAI's manufacturing division under the assumption that no design changes were likely before production.

[9]IG JAS share of the contract is 60 percent. The rest is for government furnished equipment (GFE), including communications, IFF, EW, and other electronic equipment, and all munitions other than the gun. All sorts of sophisticated munitions are envisioned for the *Gripen*, including submunition dispenser pods, laser guided air-to-surface missiles, and so forth. The government negotiated equally demanding contracts with the suppliers of GFE.

[10]FSD is projected to take ten years, from 1982 to 1992. The first 30 production aircraft are then to be manufactured and delivered by 1995.

[11]For example, the contract specifies Mean Time Between Failure (MTBF) rates for major components.

penalties for nonfulfillment. Very close government monitoring of the program is specified. Seven major program reviews are envisioned, the first five 18 months apart, the last two 12 months, requiring extensive contractor documentation. These reviews are not related to any technical milestones or progress. Little flexibility in funding or in technical specifications allowing "work-arounds" is permitted.

Both the Israelis and the Swedes entered into major FSD programs without the benefit of early austere airframe prototyping, confident that at least in the area of the basic flight vehicle, wind tunnel testing, computer simulations, and paper studies had reduced the risk to moderate or low levels. The Swedish government, however, attempted to further protect itself with a stringent contract transferring most of the financial risk associated with technological uncertainties or problems to industry. The contract rigidly specifies performance requirements and imposes substantial reporting and documentation requirements on industry. It therefore violates several other precepts often associated with an austere prototyping approach: mission rather than performance specifications, minimal government interference and reporting requirements, and the predominance of small independent industry design teams.

Although the *Lavi* contract appears to have been considerably more flexible, particularly in R&D pricing, it was nonetheless a far cry from the few pages of mission requirements provided the contractors on the U.S. Lightweight Fighter (LWF) development program.[12] Indeed, the technical specifications for the *Lavi* ran somewhere between one and two thousand pages.

The Israelis and Swedes largely ignored another concept often linked to early austere prototyping. Through necessity, Dassault traditionally built slowly on past efforts in accordance with the concept of design incrementalism. Although both IAI and Saab had experience with delta/canard configurations, the Israeli firm had never developed a high-performance fighter from scratch, and its Swedish counterpart hadn't developed an entirely new airframe for twenty years.[13] Both programs incorporated substantial concurrencies in air vehicle and major

[12]The result of acquisition reform initiatives advocated by Secretary of Defense David Packard in the early 1970s, the U.S. Air Force LWF technology demonstration program is often held up as a model for competitive austere prototype development before FSD. This program eventually led to the full-scale development of the General Dynamics F-16 and the McDonnell-Douglas/Northrop F-18 derived from the YF-16 and YF-17 prototypes. See Smith, et al., 1981.

[13]While superficially similar in general configuration, the *Kfir* and *Viggen* must be characterized aerodynamically as belonging to an earlier generation of fighters. Saab of course has developed and fielded many highly capable combat aircraft, including the J29, J32, J35, and A+J37.

subsystem development and in acquisition phasing, most notably in the overlapping of FSD and production. The Swedish and Israeli strategies emphasized the total weapon system development approach, with simultaneous development of all the major subsystems and components of the overall weapon system.

If two programs ever existed that clearly contrast with the traditional Dassault austere prototype approach to aircraft development, they are these two programs. The next section reviews their progress, venturing some observations that link program performance to the acquisition style and contracts adopted.

FSD OF THE NONMISSIONIZED AIR VEHICLE

From its approval in 1982 through its cancellation in late 1987, the *Lavi* FSD program generated intense controversy. Most of that controversy concerned program costs, U.S. funding levels, and differences of opinion regarding the most cost-effective use of Israel's limited development and acquisition resources. None of these controversies bear directly on the relative merits or demerits of the acquisition R&D strategy adopted by the *Lavi's* developers. Yet, the intense emotions they aroused make objective assessment of the R&D program by outside observers even more difficult than usual, because opponents of the program both in Israel and abroad understandably adopted any available tactic to undermine or discredit it. While the *Gripen* program has not become a major source of controversy outside Sweden, it is causing growing controversy within that country. Consequently, similar problems arise in assessing its acquisition approach. Nonetheless, it is clear that both programs have experienced unexpected technical problems in the basic air vehicle development phase of FSD that have far surpassed initial expectations in their severity and that have caused moderate to major development schedule slippage and cost growth. Further, these problems appear to be far more severe than those experienced during the *Rafale* A and EAP flight demonstration programs.

Like the *Gripen* program, the *Lavi* FSD program originally envisioned a three-and-a-half-year flight test program employing five flying prototypes, the first two of which would validate flight characteristics and compatibility with munitions and other underwing stores, and therefore would not require mission avionics and other combat subsystems. This part of the program was expected to be routine and fairly low risk. Engineers worried much more about the problems that might be encountered on prototypes three through five that would be used for mission avionics integration and operational testing.

Since the government canceled the program before the completion of the third prototype, it is difficult to know whether these concerns were warranted. Engineers clearly experienced several serious, unexpected problems on the routine early part of the program, testing basic air vehicle flying characteristics. These problems concerned both the design and construction of the main wing, as well as the related area of flight control system hardware and software development.

IAI had originally planned to equip the *Lavi* with an advanced all-CFC bonded wing. IAI negotiated a subcontract with Grumman Aircraft Corporation for detail design and manufacture of the first composite wing sets. Unlike Dassault or BAe, however, neither IAI nor Grumman had much experience with large CFC structures. Neither bothered to test a prototype wing structure or try out such structures on a flying testbed or a pre-FSD technology demonstrator vehicle, as had the two European firms. The result was disastrous. The first wing, built to production standards, failed catastrophically during static ground testing.

Deeply concerned over the vulnerability of the *Lavi* program to cancellation and the political ramifications of schedule delays, following the set-back of the static ground test failure IAI quickly dispensed with the all-composite wing, and settled for a more conventional, lower-risk CFC-skinned wing over a traditional frame constructed of metal spars and ribs. However, the *Lavi's* wing problems were not over.

A potentially much more serious and disruptive problem emerged after the quick-fix of the CFC wing problem had been implemented: Continuing wind-tunnel testing revealed that the final engineering drawings released to Grumman did not reflect the optimal wing design. It soon became evident that the *Lavi* would not be able to meet its operational requirements unless engineers enlarged and reconfigured the wing. To avoid even greater schedule slippage in the flight test program, IAI decided to go ahead and complete manufacture of the first and second prototypes equipped with the smaller, incorrectly designed suboptimal wing. When the larger redesigned wings became available, they would be sequentially retrofitted back onto the first two prototypes in a manner that permitted at least one prototype to remain active in the flight test program. This solution required a reshuffling and compression of the test objectives of the early prototypes. To provide sufficient test data to complete aerodynamic validation with the redesigned wing, it became necessary to rededicate the third prototype to the aerodynamic flight test program, delaying missionization and avionics integration until the fourth prototype.[14]

[14]This change may also have reflected a more realistic assessment of the time needed to develop the avionics subsystems required to missionize the prototype. Prototype 02,

These two wing problems, possibly combined with other aerodynamic design anomalies, contributed to major difficulties in the development of the flight control system. As in the case of composite manufacture, IAI had little direct experience with the development of control configured vehicles (CCV) like the *Lavi* and the advanced digital Fly-By-Wire flight control systems necessary to control them. Yet the *Lavi's* FBW system required the largest and most complex software development effort in that area to date. Obviously flight system hardware and software development is closely linked to and critically dependent on the platform performance dynamics and specifications. Every configuration change requires substantial modifications and redevelopment of the basic flight control laws on which the FBW software is based. Not surprisingly, the two major wing changes necessitated huge changes in the flight control laws supplied to Lear-Siegler, the subcontractor developing the FBW system.[15] Dassault and BAe, of course, benefited from the considerable experience gained with many of these technologies and problems during their FBW testbed and *Rafale* A and EAP technology demonstration programs.

The *Lavi* airframe development problems discussed above, combined with the general "friction" evident in most large-scale development programs, led to an official program delay of about four to five months—from September to December 31, 1986—in the first flight of the first prototype. According to at least one source, however, the actual delay, compared with original internal program projections, amounted to something closer to 12 months. It is difficult to assess the cost growth in the program attributable to these problems. Program managers claim that before cancellation total cost growth—after the final design configuration was frozen in 1983/84—amounted to about 10 percent in real terms. Much of this probably is attributable to the problems discussed above. One source claims that cost growth on flight control system development had already surpassed 500 percent at the time of program cancellation.

Although reliable information is difficult to obtain, the evidence suggests that the *Gripen* program is suffering from similar if not more severe problems, particularly in the development of the FBW flight control system, that have already led to substantial schedule delay and

equipped with the old wing, had first flown in March 1987. At the time of program cancellation on August 30, 1987, prototype 01 had been withdrawn from the flight test program and was in the process of being re-winged. Tests were continuing with small-winged prototype 01, while prototype 03, equipped with the new wing, was nearing completion. Despite program cancellation, IAI apparently went ahead and completed the third prototype and flight tested it as an avionics testbed.

[15]Lear-Siegler also experienced some work load and technical problems of its own making during this period.

cost growth. To date, the major causes appear to be (1) design and production problems associated mainly with large CFC structures, (2) unexpected weight growth, probably related to problem (1); and (3) difficulties validating the flight-control system software for the FBW system developed by Lear-Siegler, presumably stemming from the first two problems. IG JAS has also pinpointed development problems with the RM12 turbofan—an uprated development of the G.E.F404 engine—and difficulties in selecting primary armament for the aircraft. However, the first three interrelated problems are the major cause of program delays. The evidence suggests that, in a manner not dissimilar to the *Lavi* program, airframe configuration and weight growth problems are leading to alterations in flight control laws, thus requiring major redevelopment of flight control hardware and software.

The *Gripen* airframe is an unstable CCV with fully flying movable canards and nine other control surfaces, controlled by a three-channel FBW system with no mechanical backup. Saab, like IAI, had little hands-on experience developing such air vehicles or the sophisticated FBW systems necessary for flight control. Although Saab began experimenting with a one-channel FBW system with a mechanical backup on a *Viggen* testbed in the early 1980s, its computers and software differed considerably from those being developed for the *Gripen*. Engineers found that little information from the test-bed program was relevant to the new development effort.

One-third of the *Gripen* airframe is manufactured from composites—including the wing skin, fin, canards, and inlets—with which IG JAS has little experience.[16] The wing is constructed primarily of composites, with only the major components associated with load introduction—such as wing root fittings and pylon ribs—constructed from metals. BAe is producing the first three prototype wing-sets, all of which are manufactured to production standard. From the fourth prototype on, IG JAS planned to manufacture all wing-boxes and skins.

While the Swedes apparently avoided some development and manufacturing problems by subcontracting the CFC wing to BAe, there are indications that, as on the *Lavi* program, other design problems are making fulfillment of contract performance specifications difficult. Both Rockwell and BAe had originally been subcontracted to assist with the wing design but initially had difficulty meeting the shifting technical requirements of IG JAS. Nonetheless, project managers froze the wing design early in the program. Saab engineers now note that on advanced CCV designs, it is difficult to adjust the wing design configuration to compensate for weight growth and changes in the center of

[16]Some *Viggens* have been built with CFC fins.

gravity once the design is frozen and prototype manufacture has begun.[17]

As in the *Lavi* program, changes in design configuration in attempts to meet original requirements clearly have necessitated numerous modifications in the flight control laws, causing costly delays in the development of the FBW hardware and software. Lear-Siegler began receiving flight control law data from IG JAS in 1983. Before the flight test program, the Swedish consortium substantially changed the basic aerodynamic data package at least six times as the result of ongoing simulation and wind-tunnel testing. On average, the complexity of the software changes required by each new data package equalled about 50 percent of the original package. In other words, each new package apparently did not reflect an anticipated level of refinement of the previous package but rather seemed to indicate that the airframe developer was continuing to experiment with major design configuration changes.[18] By the end of 1987, these problems had resulted in an increase on the order of 250 percent in the cost of development of the *Gripen* flight control system. At that time, projected first flight of prototype 01 had already slipped considerably.

Under increasing political pressure caused by a burgeoning controversy over programs delays and cost growth, Saab finally launched *Gripen* prototype 01 on its maiden flight on December 9, 1988. This represented a schedule slip in first flight of at least 18 months according to public accounts, and up to as much as 30 months longer than original internal program estimates. At that time, the government was completing a major review of the program, following a submission to the government by IG JAS of a cost estimate for the follow-on buy of 110 production aircraft that was substantially higher than the "not-to-exceed" price established in the 1982 contract. In late January 1989, the government released data from the program review that showed a real program cost growth of approximately 15 percent (about $1.1 billio ·), with program unit costs for the first 140 aircraft estimated on the oruer of $54 million. The government review concluded that substantial additional funds would be required to complete the program. This money in part would have to come out of other SAF projects and from munitions, EW, and other subsystem development programs for the *Gripen* and other SAF aircraft. A final decision on production is now not scheduled to take place until 1991.[19]

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[17]BAe notes that schedule delays were caused by changes in aerodynamic loads but claims that the British firm was able to meet all contractual milestones on schedule nonetheless.

[18]Lear-Siegler claims that IAI experienced similar problems.

[19]See Brown, 1989 "Sweden," *MILAVNEWS*, NL-327, January 1989, NL-329, March 1989; "Gripen Flies Unstable," *Flight International*, December 1988; and "Gripen Flies—18 Months Late," *Jane's Defence Weekly*, December 1988.

To make matters worse, the growing controversy surrounding the program may have led IG JAS to begin the flight-test program before it had adequately solved the problems involving the flight-control system, possibly contributing to a spectacular accident that set the development program back even further. On February 3, 1989, the *Gripen* test vehicle crashed on landing after only its sixth flight. On all five previous flights, it had exhibited lateral oscillation and extreme control sensitivity exceeding that expected from ground simulation. On the sixth flight, the test vehicle experienced severe pitch oscillation on final approach, leading to the crash landing.

It is unclear at this time what long-term effect the crash will have on the ultimate fate of the program.[20] What is clear is that IG JAS still has not solved fundamental airframe design and flight-control problems that emerged very early in the FSD program, that these problems have led to major program delays well in excess of two years, and that considerable cost growth may adversely affect critical SAF programs and requirements.

SUMMARY OBSERVATIONS

Numerous aspects of the unique and difficult political, industrial, and economic situations faced by Israel and Sweden determined the acquisition strategy selected for the development of national fighter/attack aircraft. First and foremost among these is simply the tremendous effort necessary merely to persuade the national political authorities in small countries to approve and continue to support such enormously costly projects. In such circumstances, program advocates both in government and industry perceive the concept of a pre-FSD proof-testing phase with an austere prototype as unnecessarily prolonging the vulnerability of the program to parliamentary scrutiny and cancellation. In their view the best guarantee of program survival, and indeed the very survival of the nation's military industrial aerospace sector, is early commitment to FSD. Such circumstances, of course, are not directly relevant to the U.S. experience.

Yet the developers of the *Lavi* and the *Gripen* adopted their chosen development strategies also because they believed those strategies make the most sense in a changed technological environment. They argue that:

[20]The first flight of the second test vehicle, originally scheduled for April 1989, is expected to be delayed at least two months and probably more.

- advances in computer simulation and the development of sophisticated design aids such as CAD/CAM, combined with intensive wind tunnel testing, have greatly reduced the technological risk and uncertainties associated with basic airframe development;
- the development and integration of extremely sophisticated interactive avionics systems is by far the highest risk technology area in modern fighter development programs. Reduction of uncertainties in these areas is best accomplished through avionics integration labs and through the testing of fully missionized engineering test vehicles.

The first component of this argument clearly needs to be qualified, given the experience of the *Lavi* and *Gripen* developers. Expecting that only minor detail changes would be required based on the results of flight testing, IAI and IG JAS early on froze their designs and committed to production tooling and the procurement of long-lead items. Following more extensive wind-tunnel, static, and flight testing, they apparently discovered major flaws in some of their assumptions about design configuration and fabrication of large composite airframe structures. These problems contributed to serious delays in the development of flight control hardware and software, resulting in substantial cost growth and program schedule slips of two years or more in the case of the *Gripen*, and possibly the crash of the only flying test vehicle.

Although the advances in airframe technology demanded by each new fighter generation in the traditional areas of top speed and altitude have declined or stagnated, new high-risk areas of technology development may have taken their place. These include the manufacture of major composite airframe structures, novel delta wing/canard CCV layouts with a large number of control surfaces, and sophisticated FBW flight control systems. Other new developments such as stealth technology add further elements of uncertainty to airframe development. One lesson of the *Lavi* and *Gripen* programs, then, is that there are still areas of considerable technological risk and uncertainty in basic air vehicle development that cannot be reduced to insignificance from computer simulations and wind-tunnel testing alone.

What these two programs tell us about avionics development and integration is problematical, however, even though the basic developmental philosophy adopted may be sound. Neither of the programs has progressed sufficiently to make any judgment. Based on the performance of all four programs to date, however, it is possible to make additional general observations about this and other aspects of the development strategies.

IV. CONCLUDING OBSERVATIONS

Each of the programs examined in this report was shaped by a unique national military, political, economic, and industrial environment. Each had somewhat different military, technological, industrial, and political objectives. Different schedules and priorities applied to all of them. Most important, none of the programs has come close to producing a finished product; they are in the earliest stages of a FSD effort, or in the case of the *Lavi*, have been cancelled. Even if there were more data, such data are unlikely to be made readily available to foreigners for objective evaluation. Nonetheless, some tentative observations may be drawn from the views of the developers themselves and from a careful although admittedly somewhat subjective examination of the evidence.

Early, austere pre-FSD prototyping can still contribute substantially to the reduction of technological uncertainty, and thus risk, in basic airframe development. The developers of the *Rafale* A and EAP have enthusiastically embraced this approach and strongly believe in its benefits. Both the BAe and the Dassault programs produced sophisticated flying technology demonstrators in a little over three years from the time of the signing of the development contract, at a small fraction of the typical total program cost of a FSD program.[1] Furthermore, these European firms argue that their demonstrators permitted designers and engineers to take greater latitude in experimenting with unfamiliar materials and configurations that otherwise would not have been possible on FSD engineering prototypes. Such experimentation is providing useful information regarding optimal manufacturing techniques, probable cost and performance tradeoffs, and potential problem areas that will profit the FSD programs.

In many respects the objectives assigned to the first engineering test vehicles in the early phases of the *Lavi* and *Gripen* FSD programs closely resemble those for the *Rafale* A and EAP technology demonstrator prototypes. Like the British and French prototypes, the first test vehicles in the Israeli and Swedish FSD programs are also not missionized, being equipped with virtually none of the avionics—other than the flight control systems—intended for the production versions.

[1]The EAP cost about £180 million to develop and manufacture. FSD of EFA is conservatively projected to cost the UK alone about £2 billion to develop and another £6 billion to procure. If these figures prove correct, the total EAP program would account for only about 10 percent of the UK's EFA FSD costs and 3 percent of its total program costs.

These test vehicles, like the *Rafale* A and EAP, are being used primarily to verify general flight control and flying characteristics, validate aerodynamic design, and proof-test the basic airframe-engine combination. Yet the Israelis and the Swedes have spent much more time and money during this phase and seem to have already experienced far more problems. BAe and Dassault took only about three years to get their prototypes flying.[2] IAI took four and a half years. IG JAS took considerably more than six years to get its first test vehicle airborne.

This difference in program performance stems in part from fundamental differences in how the test vehicles are treated. Skilled technicians in R&D shops assembled the *Rafale* A and EAP on soft tooling. Program managers viewed them as learning devices; these aircraft were expected to be altered and modified based on the results of test flying and hardware cost/benefit analysis. When problems arose, modifications were fairly easy and inexpensive because no commitment had been made to long-lead production items or expensive production tooling.

The first *Lavi* and *Gripen* prototypes were manufactured—at least in part—on hard tooling by production workers. Developers of these test articles anticipated only minor detail changes; they were essentially intended to duplicate as closely as possible the final production article. Production design had been frozen before the completion of the first engineering test vehicles, greatly magnifying the cost and schedule implications of any changes in design or structural composition and manufacture required by subsequent testing.

In many respects, the success of BAe and Dassault arises not only from their early use of austere pre-FSD prototypes per se but also from the adoption of a broader acquisition strategy incorporating other important concepts along with—and often associated with—austere pre-FSD prototyping. In turn, many of the problems experienced by the Israelis and the Swedes during the first phases of FSD, when they were concentrating on the nonmissionized flight test vehicles, appear to be related to their failure to adhere to the basic precepts often identified with Dassault's traditional brand of prototyping, most especially

- R&D incrementalism and
- avoidance of program concurrencies.

BAe's and Dassault's projects clearly benefited from a strategy of design and developmental incrementalism in at least two areas that proved most troublesome for the Israelis and the Swedes: large

[2]As mentioned in Sec. II, the *Rafale* A actually achieved first flight less than 27 months after the beginning of development.

structures composed of carbon-fiber composite (CFC) and other exotic materials, and controlled configuration vehicle (CCV) FBW flight control systems. The British and French designed their prototypes and flight programs to accommodate learning and modifications. Furthermore, they sought smaller degrees of advancement in high-risk technologies between their hardware experience and their flight test vehicles.

This incrementalism in design and technology development was accomplished through the classic Dassault method of modifying existing airframes into testbeds for the development of a specific new component, structure, or subsystem. Both BAe and Dassault developed all-CFC bonded wings and other large airframe structures and flew them on testbeds. This approach provided them with invaluable information about the performance and manufacture of large CFC structures that considerably reduced risk and uncertainty and permitted advanced experimentation in new areas on the *Rafale* A and EAP programs. The lack of such experience was sorely missed by IAI and Grumman on the *Lavi* program, causing major program disruptions. Although the *Gripen* developers wisely sought BAe's assistance for design and development of the CFC wing, there are indications from the serious weight growth of the first prototype that at least some problems related to insufficient experience with CFC structures on the part of IG JAS.

Likewise, both BAe and Dassault accumulated much more experience with the development of CCV designs and FBW flight control systems than IAI or IG JAS. The British developed and flew a digital FBW system in a modified *Jaguar* testbed. Dassault experimented extensively with CCV designs, producing Europe's first production CCV with FBW flight control system in the late 1970s.[3] The evidence suggests that Saab's experimentation with a single channel FBW system on a *Viggen* testbed provided insufficient experience with this technology. IAI had no expertise in FBW flight control systems at the beginning of the *Lavi* program. Neither company had any hardware test experience with CCV designs; indeed, Saab had not developed a new fighter design in 20 years, whereas IAI had never developed a fighter from scratch. Nonetheless, they chose to launch directly into the largest and most challenging FSD programs they had ever contemplated.[4]

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[3]The *Mirage* 2000C exhibits neutral stability in clean configuration, but becomes unstable with underwing stores. Its FBW system is analog, with no mechanical backup.

[4]In the past both Saab and IAI had made extensive use of more conservative development approaches employing prototypes and incrementalism. To validate the all-flying double delta wing configuration developed for the Saab 35 *Draken* in the 1950s, Saab built and tested a scaled-down flight prototype. The Saab 32 *Lansen* wing was also

The two sets of programs reviewed in this report also present stark contrasts in program phasing: The *Lavi* and *Gripen* programs are total system approaches characterized by numerous R&D and production concurrencies, while the *Rafale* A and EAP are components of "phased" programs with more distinct and separate concept validation, FSD, and production periods. The Israeli and Swedish programs attempt to develop the airframe and all subsystems simultaneously while concurrently gearing up for production. Manufacture of production standard prototypes on hard tooling began for both programs before the completion of wind-tunnel testing and computer simulations, leading to costly and time-consuming problems such as the wing retrofit on the *Lavi*. Both programs envisioned the commencement of series production well before the completion of FSD flight testing. IG JAS now claims that their development strategy assumes that the initial block of 30 production aircraft will have to be extensively modified upon the completion of flight testing. Development officials privately admit that those modifications will probably be much more extensive and cost considerably more than original expectations.

It remains to be seen how much program overlap between FSD and production will be permitted on the *Rafale* and EFA programs. In the past, Dassault R&D programs at least have traditionally moved rapidly to flying prototypes and then concentrated on lengthy flight testing without any commitment to high-rate production. This has often been as much the result of political hesitation or budgetary constraints as of a conscious acquisition strategy; but both the *Rafale* A and EAP technology demonstration phases have been clearly and distinctly separated both from the earlier design concept validation phases and FSD phases.

Early, austere prototyping may still play an important role in reducing uncertainties and risks in large fighter development programs. Yet the relative success of the British and the French (so far), compared with the Israelis and Swedes, appears to depend on a broader organic strategy that goes beyond austere pre-FSD prototyping to include at least two other key elements: program and design incrementalism, and the avoidance of program concurrencies.

Furthermore, management style and organization also seem to play a role. Program officials developing both the *Rafale* A and EAP are convinced that the approach using flexible, lean management and R&D teams burdened with minimal government interference and oversight

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demonstrated on a test-bed flight vehicle. The *Viggen*, however, went directly into FSD. IAI developed the *Kfir* through a whole series of incremental design improvements on the original *Mirage* 5 design, most of which were prototyped. Indeed, the confidence these developers gained from their earlier successes led them to believe that could adopt more risky and aggressive development approaches.

benefited their programs immensely. They particularly applaud the decision of their governments to forgo detailed technical specifications and reporting requirements as a high-leverage means of enhancing program efficiency.

The benefits of greater flexibility and reduced bureaucracy can even be detected when comparing the *Lavi* and the *Gripen* programs. The technical specifications for both projects were massive and detailed. However, once underway, the Israelis reverted to their more typical extemporaneous style and continuously revised the development program as it unfolded. IG JAS, however, found itself bound in a strait jacket of incredibly detailed reporting requirements, schedule and performance milestones, and thresholds.

The *Lavi* wing problem and the flight control system difficulties in both programs illustrate this point. When the original *Lavi* all-CFC bonded wing failed and engineers discovered the wing design error, the Israelis showed great flexibility and resourcefulness by rapidly substituting a structurally redesigned wing and shuffling the entire flight test program, so that flight testing could continue uninterrupted while the newly designed wing was manufactured and retrofitted. Likewise, when major problems began to emerge in the development of the flight control system—in part stemming from the wing design problems—a decision was made to proceed with the development of the flight control system during flight testing, rather than keeping the prototypes grounded until a fully capable flight system was checked out. Thus, when the first prototype first flew, its flight control system was in an extremely immature state of development; for example, it was so undeveloped that it did not permit supersonic flight.[5] Throughout the initial flight testing, IAI slowly expanded the flight envelope and the demands placed on the flight control system, as that system evolved toward higher capabilities. By the time of program cancellation, enormous development progress had occurred on the flight control system without catastrophic disruption or delays to other flight test objectives.[6]

The Israelis seem to have gained considerably from this flexibility. By reducing the delay and continuing the flight test program with the small wing on prototypes 01 and 02, and by forging ahead with a very immature flight control system, engineers could begin gathering extremely beneficial flight performance information after only minor delays. This flexibility and willingness to develop quick work-arounds

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[5]Both the *Rafale* A and EAP went supersonic on their maiden flights.

[6]This approach may also ultimately have been adopted by IG JAS, with much less satisfactory results, if it is determined that the crash of prototype 01 in February 1989 was the result of an insufficiently developed FBW flight control system.

clearly permitted the program to advance at a much faster rate than otherwise would have been the case, holding program delays to a minimum.

This conclusion can be confirmed by comparing the *Lavi* experience with that of the *Gripen*. All *Gripen* systems are required by contract to meet detailed and very extensive performance and reliability specifications at periodic milestones for the program to continue. According to at least one subcontractor, much of the two-year delay already experienced in the program is the product of inflexible government oversight and demands for strict adherence to the contract warranties and guarantees. Regarding the flight control system, the *Lavi* problems initially may have been potentially more disruptive than those confronting IG JAS. For example, some of the *Gripen* flight control difficulties relate to areas not critically important to flight testing, such as the BITE (Built In Test Equipment) maintenance capability of the system. Yet strict adherence to contract warranties and performance milestones requires full development of this capability before flight testing. Indeed, it is claimed that the *Gripen* could already have begun flight testing and made considerable development progress if the Swedish authorities had taken a more relaxed view toward fulfillment of all requirements before first flight, as did the Israelis.

In conclusion, the initial subjective impressions from these programs appear to confirm the view that early, austere prototyping of the airframe, combined with design incrementalism, clear separation of program phasing, and flexible, lean management structures with minimal government interference, all contribute to more successful outcomes in large-scale fighter R&D efforts. Unfortunately, none of the programs examined so far has shed any light at all on the scale and importance of these apparent benefits relative to the entire development process. Does early, pre-FSD, austere airframe prototyping contribute decisively to substantially more efficient and cost-effective FSD programs? There is no way to tell based on the experience of these four programs, since the three surviving programs have only just entered FSD and at most have not progressed beyond initial flight testing of the airframe/engine combination.

These programs cast doubt on only one element of the *Lavi* and *Gripen* development strategies: that modern computer assisted design tools, computer simulations, and extensive wind-tunnel testing can necessarily eliminate most of the uncertainties in basic airframe development before the manufacture of a test item. What these programs tell us is that in certain circumstances basic airframe development still carries sufficient risks and uncertainties to warrant the manufacture and flight testing of an airframe prototype before FSD.

But these programs do not necessarily invalidate the contention of the Israeli and Swedish developers that avionics development and integration—the areas of highest technological uncertainty and risk—can be developed and adequately tested only in avionics ground labs and on fully missionized prototypes that are essentially pre-production FSD engineering test articles. The severe problems experienced on both the *Lavi* and *Gripen* programs with development of the FBW flight control system may be just a hint of the magnitude of the difficulties that can be expected when the full avionics suites enter into advanced stages of development and integration. Since avionics development costs may rise to 50 percent or more of total R&D costs, determining the most efficient avionics development and integration strategies is critically important. The huge FSD costs currently projected for both EFA and the *Rafale* D—in the neighborhood of $10 billion for the former and over $6 billion for the latter—suggest that the bulk of the cost, and thus research effort, is expected to take place once FSD begins and will be heavily related to subsystems development and integration.

Past and ongoing RAND research demonstrates that major avionics subsystems such as radars and mission computers need to begin development considerably earlier than the airframe/engine combination, and should be cycled through several developmental iterations to attain acceptable levels of reliability.[7] If these research results hold true, then none of the four programs examined in this report may have been optimally structured. FSD contracts for the major avionics subsystems for the *Lavi* and the *Gripen* were not signed until *after* the signing of the overall development contract. At the time of program cancellation, two *Lavi* prototypes had entered the flight test program, yet the first prototype *Lavi* radar had not yet made its maiden flight on a transport aircraft testbed. In the case of the *Gripen*, some of the weapon systems have not even yet been designated or defined, contributing to the difficulty in developing the avionics suite. The EFA consortium has still not selected and negotiated FSD contracts for the engine, radar, and other major subsystems. In all likelihood, most of the critical subsystems will be entirely new developments, requiring high-risk R&D efforts.[8] Thomson-CSF and Electronique Serge Dassault have developed new-generation radar technology demon-

[7]See McIver et al., 1974; Gebman and Shulman, 1988.

[8]Rolls-Royce has proposed a derivative of the existing RB199 turbo-fan for the EFA, but the consortium will probably select the all new collaborative EJ2000 proposed for development by the Eurojet international consortium. For the EFA radar, a derivative of the Hughes APG 65 has also been proposed but is also likely to be rejected in favor of a new collaborative development.

strators, but it is unclear how applicable they will be to the production radar selected for the *Rafale* D. The SNECMA M88 turbofan is also still in the early phases of development. Thus,

- Use of an R&D strategy employing early pre-FSD austere airframe prototyping, and other associated concepts, can contribute substantially to reducing uncertainty in the early phases of FSD, but may not be sufficient to assure a successful fighter R&D effort overall unless other strategies specifically tailored to addressing the problems of avionics and other subsystem development and integration are also adopted before and during FSD.

These strategies may include extensive testing with a fully missionized engineering test article that duplicates the final production version as closely as possible. But austere pre-FSD prototyping probably will be of little use in this area.

- Along with the incorporation of "phased" acquisition and initial low-rate production to reduce the costs and disruption of changes flowing from operational testing, a combination of pre-FSD austere prototyping and missionized FSD prototyping may both be required to meet the new challenges arising in the changed acquisition environment of the late 1980s.

Appendix

PROTOTYPE PROGRAM OUTLINES AND TECHNICAL DESCRIPTIONS

EAP

At the Farnborough Air Show in September 1982, the UK Ministry of Defence announced plans to launch a combat aircraft technology demonstrator development project—the Experimental Aircraft Program (EAP). This program was intended to demonstrate and proof-test advanced technologies that would benefit a new combat aircraft for the 1990s. The original participants of this program included British Aerospace (BAe), Messerschmit-Boelkow-Blohm, Aeritalia, and the UK government.

British Aerospace and the UK MOD signed a contract in May 1983 for the development and construction of a single technology demonstrator aircraft. Three years later, on April 16, 1986, BAe rolled out its EAP demonstrator. The EAP first flew on August 8, 1986.

Total development and construction of the EAP cost £180 million. The British MOD provided just under half of the funding; the remainder came from industry. £115 million was spent on the airframe and £65 million on avionics and equipment.

Description

- The EAP is a single seat, twin engine, highly agile air superiority combat aircraft with compound delta wings and all-moving canard foreplanes.
- It is powered by two Turbo-Union RB-199 engines each with a thrust of 17,000 lb.
- The EAP is controlled by a GEC Avionics quadruplexed full authority digital flight control system, which manages 13 separate control surfaces.
- All of the avionic systems are linked together through two MIL STD 1553B digital databuses, which can transmit up to 1 million bits/sec of data.

- The EAP has an advanced electronic cockpit, which includes three high resolution color Multi-Function Displays and a GEC Avionics wide angle holographic HUD (Head Up Display).
- The Martin-Baker pilot's seat is reclined 25 degrees.
- The control stick is mounted in the center enabling use by both hands.
- Carbon fiber composites make up 40 percent of EAP's surface area and 25 percent of its weight.
- The stealth aspects of the EAP are only those that are inherent in its design and use of composite materials.
- The EAP is equipped with the Lucas DECU 500 full authority digital engine control system.
- There is no weapon or radar system on the EAP.

Specifications

- Length : 14.7 m (48ft 3in)
- Span : 11.17 m (36ft 8in)
- Height : 5.52 m (18ft 2in)
- Weight : Empty—10,000 kg Clean Gross—14,151 kg
- Wing Area : 52.0 m^2
- Speed : Mach 2+
- Angle of Attack : 30 degrees

RAFALE

Avions Marcel Dassault Breguet Aviation designed and constructed the *Rafale* A technology demonstrator, an outgrowth of the ACX Experimental Combat Aircraft proposal. The ACX was intended to proof-test new technologies that could be employed in combat aircraft of the 1990s. The *Rafale* demonstrator is Dassault's 92d prototype in 40 years.

The French Ministry of Defence approved the program in April 1983. Construction of the demonstrator began in March 1984. The French government and industry each funded 50 percent of the costs. Dassault rolled out the *Rafale* A on December 14, 1985. First flight took place on July 4, 1986, six months ahead of schedule.

The French government approved FSD of the *Rafale* D in principle in mid-1987. The *Rafale* D will be smaller, shorter and lighter (BME 8.5 tons) than the *Rafale* A. It must meet both the French Air Force and Navy operational requirements. It will replace the *Mirage*, *Super Étendard*, and *Jaguar*. Five FSD prototype aircraft will be built starting in 1988. The *Rafale* D should be operational in 1996.

Description

- The *Rafale* is a single seat, twin engine, naturally unstable aircraft. It has delta wings with shoulder-mounted active canard foreplanes.
- It is powered by two General Electric F-404 engines with 16,000 lb of thrust each. SNECMA is developing a new engine for the *Rafale* D with 19,000 lb of thrust. A demonstrator M88 engine is scheduled to fly in 1989.
- The *Rafale* is controlled by a quadruplexed digital flight control system. There are 17 separate control surfaces.
- The Electronique Serge Dassault (ESD) Digibus digital databus links together all of the avionics systems in the *Rafale*.
- The systems in the cockpit are designed to substantially reduce pilot workload. The primary display is a Thomson CSF wide angle holographic HUD. Thomson CSF also provided the main Multi-Function Display (MFD) positioned at eye-level. The two multi-function Head-Down Displays by SFENA are positioned along each side of the main MFD.
- Crouzet provides the voice alarm warning system and is developing a voice control system for the *Rafale* D.
- The Martin-Baker ejection seat is reclined to an adjustable angle of 30–40 degrees.
- The control stick and throttle are located on the side.
- New materials—carbon fiber composite, Kevlar composite, aluminum-lithium alloy, and SPF/DB titanium—represent 35 percent of the structural weight and their use results in a 20 percent weight reduction over conventional materials. Carbon fiber composite is used extensively; the wings and 50 percent of the fuselage are CFC.
- The general design of the *Rafale* and use of composite materials minimize its radar signature, but it is not a stealth aircraft. The semi-ventrally located air intakes were designed to reduce the frontal radar signature.
- There is no radar on the *Rafale* A. Thomson CSF and ESD are in competition to develop a new radar for the *Rafale* D.
- The *Rafale* A is equipped with a single 30mm cannon and 12 external hardpoints. The internal armament on the *Rafale* D will also be one 30mm cannon. The external armaments can be carried on eight under-wing and six under-fuselage hardpoints.

Specifications

- Length : 15.8 m
- Span : 11 m
- Weight : BME—9500 kg combat veight : 14,000 kg
- Wing Area : 47 m^2
- Speed : Mach 2
- Angle of Attack : 30 degrees
- Internal Fuel Capacity : 4250 kg

LAVI

The *Lavi* is a highly maneuverable, highly survivable, multi-role combat aircraft optimized for ground attack. It was intended to replace the *Skyhawks* and *Kfirs* in the Israel Air Force. Development studies began in earnest in early 1980. IAI froze the final design configuration in 1982 and the weight and avionic systems a year later. The government authorized FSD in 1982 and construction of the first of five prototypes began late in 1983. The first three prototypes were intended to validate the basic airframe/engine combination, and the last two were intended to proof-test avionics development and integration. IOC was projected for 1992.

IAI rolled out *Lavi* prototype 01 on July 21, 1986. Its maiden flight was on December 31, 1986. The second prototype first flew on March 30, 1987. However, the government cancelled the *Lavi* program on August 30, 1987.

Total development costs for the *Lavi* were estimated to be $2.5-$2.7 billion at the time of cancellation. Of the $1.3 billion spent on development before the cancellation of the *Lavi*, over 90 percent was contributed by the U.S. The Pentagon estimated that the total program cost for the *Lavi* would have amounted to about $10 billion with a flyaway cost of $22.1 million per aircraft. There was much debate within Israel and the U.S. about whether Israel needed to develop its own aircraft indigenously at such a high cost, eventually leading to the cancellation of the program.

Description

- The *Lavi* is a single seat, single engine, delta-canard configured combat aircraft with all-moving canard foreplanes. A two-seater training version was also designed.

- The aircraft is powered by a single 91.7 kn Pratt & Whitney 1120 engine with a thrust to weight ratio of 1.1:1.
- The *Lavi* is controlled by a Lear Siegler quadruplex digital flight control system equipped with nine independent control surfaces.
- All of the avionics systems are linked together by two MIL STD 1553B digital databuses.
- The electronic warfare and communications systems were contracted to Elta Electronics.
- The cockpit was designed for optimum pilot-aircraft interface with much input from IAF pilots. There are three Multi-Function Dispensers and a wide angle holographic HUD. El Op produced the Hughes HUD under license. Elbit Computers, Ltd. was responsible for integration of the display system.
- The Golan Industries' license-built Martin-Baker ejection seat reclines to a conventional 10 degrees.
- The stick and throttle are centrally positioned enabling use by both hands.
- Composite materials make up 22 percent of the *Lavi*'s structural weight. Carbon fiber composite wings were designed and produced by Grumman. IAI produced some of the other CFC structures.
- The stealth aspects of the *Lavi* are inherent in the design and use of composite materials. The small size, smooth outline, and deeply buried engine all help to reduce radar signature.
- A new multi-mode, pulse-Doppler radar for the *Lavi* was being developed by Elta Electronics. A prototype of the new radar flew in 1987.
- A French-developed 30mm DEFA cannon is mounted on the starboard wing root. There are four under-wing and seven under-fuselage hardpoints for external armament. AIM-9L Sidewinders are fitted at the wingtips.

Specifications

- Length : 14.57 m
- Span : 8.7 m
- Height : 4.78 m
- Weight : Empty—6942 kg T/O—9900 kg
- Max Speed : Mach 1.8
- Wing Area : 33.05 m^2
- Max Fuel Capacity : Internal—2721 kg External—4164 kg
- g Limit : +9

GRIPEN

The JAS 39 *Gripen* is Sweden's multi-role combat aircraft for the 1990s. The three roles of the aircraft are represented in its name—JAS (Jakt/Attack/Spaning: fighter/attack/reconnaissance) 39 *Gripen*. It is Sweden's first new frontline military aircraft in 21 years as well as being its largest defense program ever. The *Gripen* is intended eventually to replace all Swedish Air Force (SAF) *Viggens* and *Drakens*.

IG JAS, a consortium composed of SAAB-Scania, Volvo Flygmotor, Ericsson, and FFV Aerotech, was formed in 1980 and is the main contractor for the development and production of the *Gripen*. On June 3, 1981, IG JAS submitted proposals for this new combat aircraft to the Swedish Defence Material Administration (FMV). One year later, on June 30, 1982, the government authorized FSD. Government and industry signed a fixed-price contract for SEK 24.9 billion (about $3.5 billion) for the first 30 production aircraft, including five prototypes. The contract also included a commitment for 110 more aircraft by 2000. By 1987, funding had risen to SEK 41 billion (about $6 billion).

Construction of the prototype began in 1984. Formal roll-out took place on April 26, 1987. The first flight was to follow a few months later. However, technical problems delayed first flight over two years to December 1988. Prototype O1 crashed in February 1989. IG JAS insists that the operational date of 1992 can still be met.

Total development costs for the *Gripen* are estimated to be on the order of $1.6 billion and estimated program costs through 2000 is at $6.43 billion. The expected total production run is for 280–300 aircraft by 2015, with another 30 two-seater training versions being considered. The *Gripen* is anticipated to absorb about one-third of the budget of the Swedish Air Force from 1987–1992.

Description

- The *Gripen* is a single seat, single engine, multi-role combat fighter. It has a delta-canard configuration with all-moving canard foreplanes for improved maneuverability.
- The aircraft is powered by a GE F-404 engine modified by Volvo Flymotor into the more powerful RM 12 engine designation. The engine was modified for single-engine operations, higher bird strike tolerance, and increased thrust. Volvo will take over production of the RM 12 in 1991 when development is expected to be completed.
- A Lear Siegler triplex flight control system is installed in the *Gripen*. Each channel in the system is backed up by an analog channel. There is no mechanical backup.

- The electronic display system consists of three Ericsson HDDs and a Hughes wide angle holographic HUD.
- The cockpit has a Martin-Baker ejection seat reclined to 28 degrees and a centrally located control stick.
- All systems are controlled by an Ericsson SDS 80 standardised computing system consisting of 30 microcomputers.
- All systems are linked together by three MIL STD 1553B digital databuses.
- Carbon fiber composites (CFC) make up 30 percent of the airframe structure resulting in a 25 percent savings in weight.
- British Aerospace has provided the first three sets of CFC wings for the *Gripen* prototypes. Production of the wings will be transferred to SAAB.
- FFV Aerotech is developing ground support and maintenance equipment.
- Ericsson is developing a multi-mode, pulse-Doppler radar that is intended to be 60 percent of the size of current Swedish *Viggen* radar with three times the power.
- The *Gripen* is equipped with an internal 27mm Mauser cannon. There are external stations for air-to-air missiles, air-to-surface missiles, and anti-ship missiles as well as Forward Looking Infrared (FLIR) and reconnaissance pods.

Specifications

- Length : 14.1 m
- Span : 8.0 m
- Height : 4.7 m
- Weight (T/O) : 8,000 kg
- Speed : Supersonic at all atitudes
- g Limit : +9

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